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An Examination of the Feasibility and Design Limitations of Laminate Tooling for Pressure Die-Casting

By

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Abstract

Within the context of Rapid Tooling a new field of research has emerged called Laminate Tooling. This concept was explored and evaluated and ultimately led to the identification of a suitable field of application. This field is the Pressure Die-casting industry.

Laminate Tooling for Pressure die-casting forms the starting point for this thesis with the identification of the potential problem faced by the die designer when validating a die design for the actual production tooling. At present there exists no such process, in the die-casting industry, to undertake such validation. Based on its scalability, low cost and robustness, the author shows that Laminate Tooling could address this problem.

With this objective in mind, a structured, experimental, approach was initiated to address two research questions. Firstly, could a laminate die-cast die be designed and constructed and then run on a production die-casting machine without premature failure? Secondly, if a laminate tool could withstand this extreme casting process, what would be the design limitations of such a tool?

Experiments were conducted in which it was shown that an un-bonded laminate tool constructed from 1mm thick H13 tool-steel sheet could withstand High Pressure Die-casting of aluminium alloy LM24 on two production die-casting machines. A total of 90 shots were taken with no undue degradation in the tool.

The design limits were then explored through the close observation of the effects of deflection and potential permanent deformation, during the casting cycle, on individual laminate protrusions incorporated into the die design. Given the current design of the laminate test-die, no minimum height, at which permanent deformation occurred, was found.

Therefore, the outcomes of the research were that Laminate Tooling could be used for High Pressure Die-casting and given the chosen design of the die there were no design limitations. Further research is required to examine if design limitations would occur given different designs, sheet materials or geometries/aspect ratios.

Chapter 1: Introduction

1.1 Introduction

The research in this thesis has initiated work on the Laminate Tooling process for high-pressure die-casting. Laminate Tooling is a relatively new concept and one of a group of emerging technologies, which are part of the extensive efforts, globally, to enhance the product development process. These technologies are known as "Time Compression Technologies" which aim to reduce the time it takes to conceive a design, test it and then manufacture it. A fundamental shift in the way which the product development process is perceived is required. For example, the following are recommended:

- All the manufacturing functions must be involved in the design input.
- As many iterations of a design must be assessed before a design is 'frozen'.
- All the manufacturing functions should implement the product development simultaneously.
- All the manufacturing functions must be enhanced to achieve rapid product development.

This last point is crucial as a common misconception of Time Compression or Concurrent Engineering (as it is also known), is that to achieve this aim, only the design process itself needs to be addressed. If the design function alone is enhanced, using for example, Computer Aided Design (CAD), then a severe bottleneck may appear in the remainder of the manufacturing functions (i.e. prototyping, tooling and manufacture), as they are required to cope with this change of pace. To overcome this bottleneck, a series of technologies have been developed, over the last decade, which address the speed in which the remaining manufacturing functions perform their role.

These technologies are currently grouped under two categories - Rapid Prototyping and Rapid Tooling. It is these, which form the starting point for this research. The distinction between the two is that 'Rapid Prototyping' attempts to decrease the time taken to produce a prototype of a product, whereas 'Rapid Tooling' attempts to speed up the tooling for a product. There is however, a cross over between the two, as Rapid Tooling can either produce a tool to generate prototypes or, as in the case of this study, produce a tool capable of being used in the production environment.

This work is focused on one particular process within Rapid Tooling, called "Laminate Tooling". Laminate Tooling can be used for a variety of moulding and forming applications. Many of these applications will be discussed in this thesis and have been gathered through the author's own experience in the development of this technique, which culminates in the identification of one particular application domain which appears suited to Laminate Tooling. This is the pressure die-casting industry and, more specifically, for die-cast die design validation.

1.2 Definition of Problem

Die design verification is an area where currently no methods exist to assess behaviour or performance, until the production die is in full production. This is an area of development that the author, in conjunction with die designers in industry, identified as crucial to the pressure die-casting industry, as it moves towards shorter production runs to fill niche markets.

To maintain a competitive edge in the modern business culture, it is becoming increasingly important for die-casters to actively seek out new applications for pressure die-cast products. Particularly, as they have to compete with the growing injection moulding market for engineering polymers and the developing 'composites' industry. This can only be done by introducing new processes that enhance the 'Time-to-Market' ethos within the pressure die-casting industry. Laminate Tooling could offer some solutions to this problem.

Laminate Tooling is sturdy, scaleable, quick and cheap to produce and is generated directly from a 3D-CAD model. This research suggests that it could overcome all the problems associated with conventional prototype moulding techniques, and could perform, as well as, a full production tool, producing full castings in numbers, inconceivable by conventional pressure die-cast prototyping techniques. Probably the most important benefit of this approach is that, it is the first to examine a prototype tool run on die-casting machinery actually used for full-scale production.

A laminate tool for pressure die-casting could be used for a variety tasks, including:

- Appraisal of the design under production conditions.
- Assessment of heat transfer and shrinkage during cooling.
- Most effective layout of cooling channels.
- Effective gate and runner design.
- Exchanging laminates to introduce new features to the die.

- Exchanging laminates to change orientation of internal detail of the die.
- Multiple iterations before the final 'design freeze'.
- Faithful reproduction of die-cast parts, for fit, form and function testing.
- Effectiveness of the ejection system in the production tool.
- Potential for using the tool for short production runs

Existing prototyping techniques attempt to reproduce the actual part which will ultimately be cast. It will be shown that the implementation of Laminate Tooling could be the first attempt to prototype the dies themselves and can be considered a combination of both prototyping and Rapid Tooling.

In line with the potential benefits this process could offer the die designer, there are two fundamental research questions that need to be addressed.

1. Is a laminate tool capable of withstanding the harsh environments associated with the pressure die-casting process?
2. What would be the design limitations of such a tool?

1.3 Aims and Objectives of Thesis

In consideration of the potential benefits which Laminate Tooling could offer the high pressure die-cast industry, the overall aim of this thesis is:

To examine the feasibility of Laminate Tooling for high pressure die-casting.

Given this and the research questions stated before, the objectives are specifically:

Objective One - To establish whether an un-bonded laminate tool can be designed, constructed and then run on a production pressure die-casting machine to allow the production of multiple castings from that die.

Objective Two - If the tool can successfully withstand this process, then look closer at the design limitations when constructing such a tool through analysis of the potential deflection in those laminates during the casting process that may result in their premature failure.

1.4 Literature Review and Research Methodology

In order to formulate the objectives a number of methods were used in line with a scientific approach to research outlined by Phillips and Pugh (1991). Literature searches continued throughout this study through the University Library system (OPAC), BIDS and the British Library.

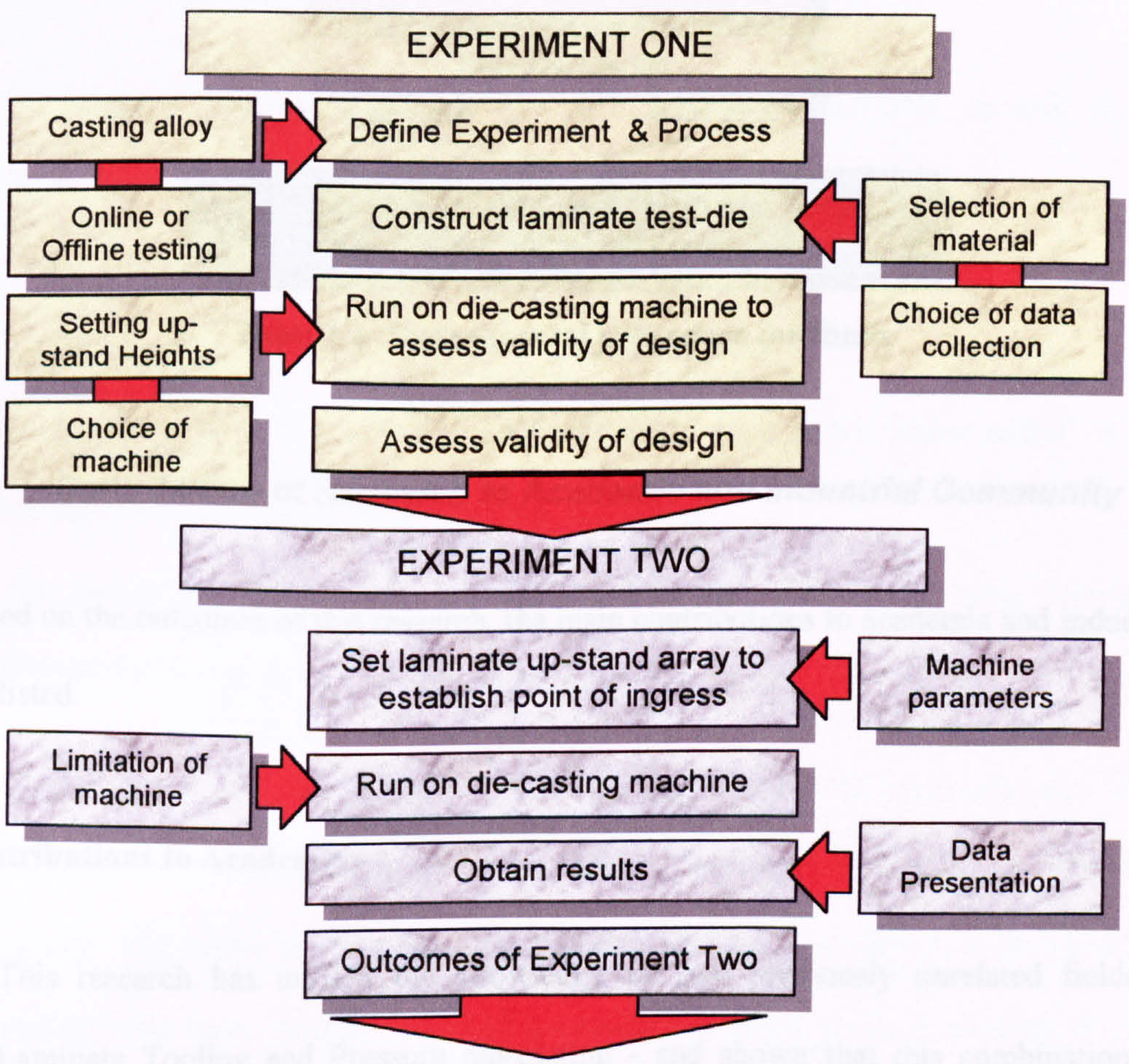
Further up-to-date information was gained, via the Internet resources through various web-sites and newsgroups including the Rapid Prototyping Mailing List (RPML). Technical information was gathered through contacts with the main producers and suppliers to the die-casting and Rapid Prototyping industry such as: Frech UK, Ramsell Naber, Klubertec Ltd, Ford Motor Company, General Motors.

Presentation and attendance of the main Rapid Prototyping and Tooling and die-casting conferences, globally, also aided information gathering. As well as, personal contact with companies and industrial representatives for interviews. Papers relating to Laminate Tooling were presented at: 3rd, 4th, 6th, 7th European Rapid Prototyping and Manufacturing conference; the SPIE Rapid product development technologies conference, (1997); the Solid Freeform Fabrication Symposium, (1997); 1st and 2nd National Conference on Rapid Prototyping and Tooling Research (TCT), (1998); and the National Die-casting Confederation conference, (1999). These papers are reproduced at the end of this thesis.

Furthermore a series of studies were conducted to identify the possible issues that may be encountered when running a tool under pressure die-casting conditions. The results of this pilot work, was used to define an experimental methodology in which an un-bonded laminate pressure die-casting tool could be designed and constructed to assess the feasibility of the process under these conditions.

In addition, the tool included a series of individual laminate protrusions on which the effects of the pressurised molten alloy, passing into the die cavity could be observed. As previously stated, it was the author's intention to identify the design limits for such a tool in this application. This could be best achieved, by identifying the point at which, a laminate tool would fail through the ingress of molten alloy between the laminates, which made up the die features. The intention was, therefore, to study the specific effect of deflection on predefined laminate protrusions, within the die cavity, that may result in the flow of molten alloy into any gap that was forced open between two laminates in an up-stand feature. Depending on the height of these laminate protrusions, at some magnitude of deflection, ingress of molten alloy would penetrate the gap rendering the die unusable.

During the actual experimental work an iterative approach was taken to the design of each experiment based on the outcomes from the previous experiment. This approach was necessary, as there were many possible outcomes and variables, which had to be constrained. Where the objectives suggest only two experiments, there were in fact three required to address all the issues encountered during each run. This is shown in Table 1.1 where Experiment Three was required to address the unusual results encountered in Experiment Two.



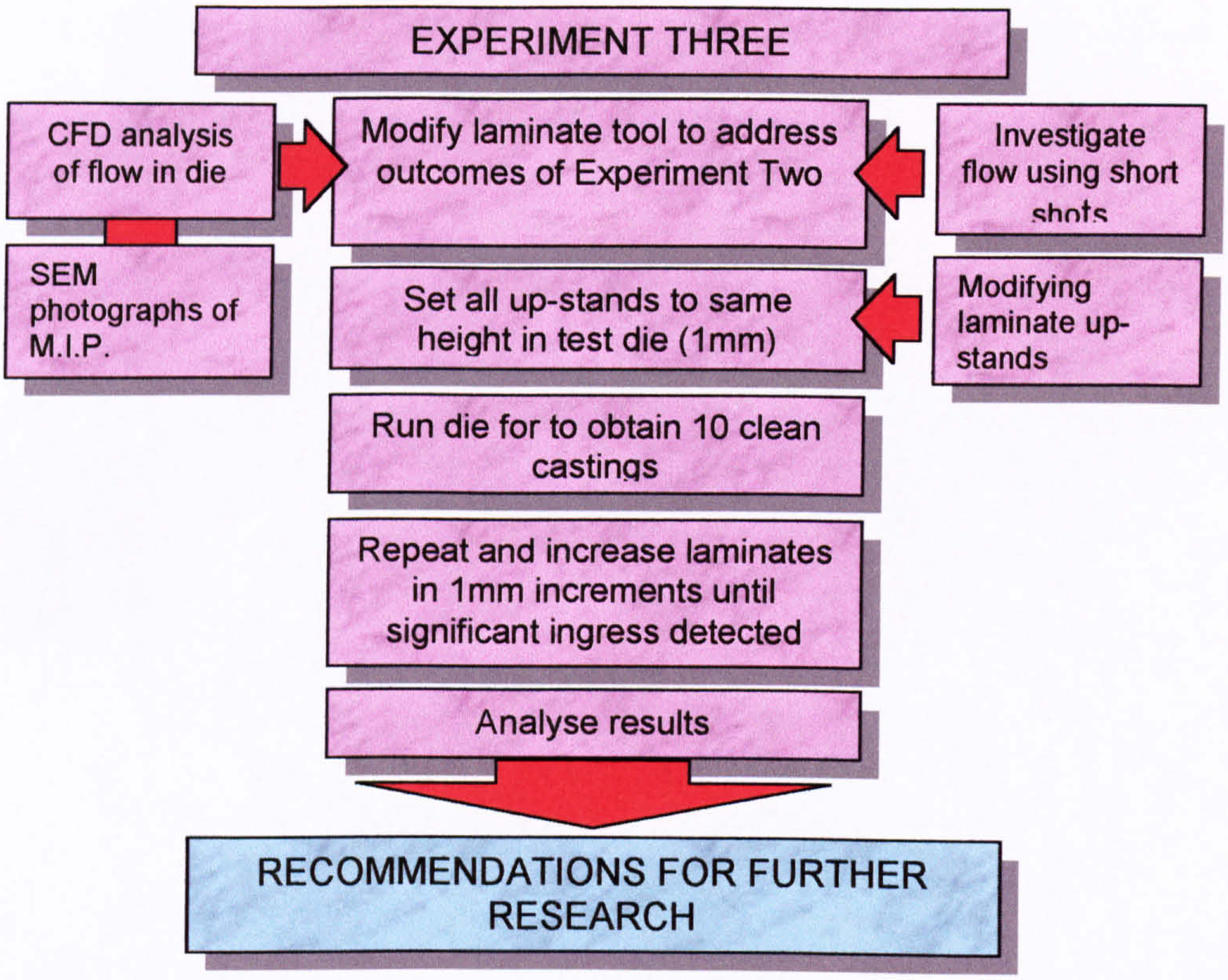


Table 1.1 Experimental procedure for thesis

1.5 *Contribution of Research to Academic and Industrial Community*

Based on the outcomes of this research, the main contributions to academia and industry are listed.

Contributions to Academia:

- This research has unified the knowledge on two previously unrelated fields - Laminate Tooling and Pressure die-casting - and shown that this combination is possible.
- An appraisal of the state of the UK pressure die-casting industry was conducted through a series of interviews with three leading experts in the field.

- A new Rapid Tooling process has been developed for the pressure die-cast industry.
- New materials and processes were identified specific to Laminate Tooling for pressure die-casting.

Directly based on the work undertaken from this project are three new projects, extending this research further into the field of pressure die-casting. Two PhD projects begin in October and will be based, partly, on the findings of this research.

Contributions to Industry:

- The specific behaviour of a pressure die-cast die was identified, as well as, the behaviour of the casting alloys used during the die-casting process.
- The study of bonding laminates for pressure die-casting applications through the application of a novel process called diffusion soldering.
- If implemented, as the author intends, there will be a direct 'value added' in the savings created through 'right first time' die design.
- The recommendations made through this research are already being extended through further research work at De Montfort University, Leicester.

An EPSRC joint funded project, with industrial collaboration, will begin this year. This project will be in conjunction with the Rapid Prototyping Group, at Warwick University. The author is a member of the Rapid Manufacturing Group, at De Montfort University, who have recently launched a consortium based research strategy for the implementation of Rapid Tooling and Manufacturing. The consortium has 24 member companies (11 Industrial, 3 Associate and 10 Materials and Equipment), three who have already made approaches to implement Laminate Tooling based research projects.

1.6 Structure of Thesis

The flow diagram shown in Table 1.2 summarises the structure for the thesis.

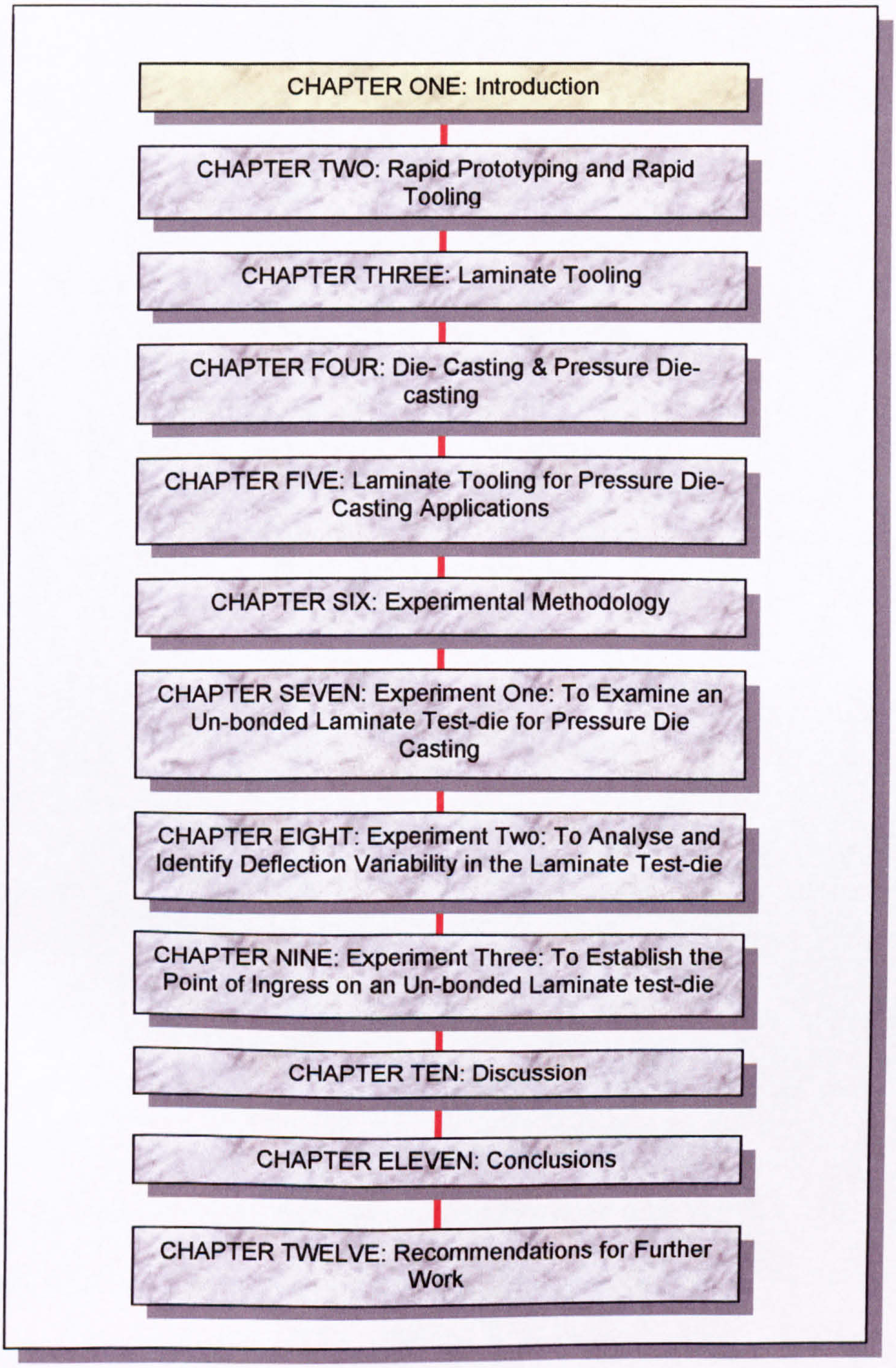


Table 1.2 Structure of the thesis

This thesis begins with a review of the current status of both Rapid Prototyping and Rapid Tooling presented in Chapter Two. It discusses how the concepts evolved and what the motivation was, to drive them to their present status. In addition, the underlying technologies are identified, through the evolution of the various computer aided design packages that feed the necessary data to the various Rapid Prototyping and Tooling processes.

The development of the Laminate Tooling process is outlined in Chapter Three. This chapter follows how the concept emerged driven by the desire for flexible, low cost, robust and scaleable tooling for various applications, which are also discussed. This appraisal concludes by, defining the key benefits the process offers over conventional tooling methods, and also, gives an indication of the current state of the research around the world.

As this research is the unification of two different technologies, Chapter Four, attempts to summarise the principle processes, relevant to this research, within die-casting and pressure die-casting. The terminology is shown and draws a distinction between the permanent moulding processes. An extensive appraisal of the industry was undertaken in which data was gathered from various sources so that comparisons could be made between the different processes, end users, and production rates for the key global markets (i.e. the US, Europe and Japan). The chapter concludes with an analysis of the key research areas identified by the North American Die-caster's Association (NADCA) as critical to the continued growth of the industry. One important area identified is the implementation of Rapid Tooling concepts into the industry.

It is the specific implementation of Laminate Tooling for pressure die-casting applications that is considered in Chapter Five. This is done by identifying the existing techniques in use to produce prototype castings within the industry, and, in particular, their shortcomings. The author then identifies the importance of, not only, having Rapid Prototyping techniques to quickly generate prototype castings but, more importantly, the industry requires a process to allow the appraisal of the actual die design used for the production run. It is this area that is identified as potentially costing the die-caster more in the long run, this is mainly due to the very high costs involved in correcting errors later on. This leads to the suggestion that Laminate Tooling could offer the die designer the opportunity to appraise multiple die design iterations before the final tool design is 'frozen'. There has never existed such a process within the field before.

The chapter concludes by identifying the various issues that would need to be addressed if such a tool were constructed, and run on a production die-casting machine. This is done through a series of assumptions, which ultimately lead to the hypotheses shown earlier in this chapter.

The experimental methodology is then shown in Chapter Six, in which the various constraints and variables are fixed leading to the design and construction of an un-bonded laminate tool specifically for the high-pressure die-casting process. In addition, the ramp features, which were used to meet the second objective are discussed, i.e. that of identifying the design limits through the study of deflection in the laminate elements within the die.

Experiment One is then considered in Chapter Seven. This experiment was designed to answer the question of whether a laminate tool could withstand the die-casting process. Observations are made over a series of seven runs generating over seventy castings. This lengthy analysis resulted in the conclusion that the test-die survived the die-casting process with no adverse affects. This experiment completely validated the Laminate Tooling concept when used as a pressure die-casting tool.

Chapter Eight, therefore, proceeded to identify the design limits for such a tool through the analysis of individual laminate protrusions deflecting in the die cavity during injection. It was hoped that the measurements taken would indicate at what protrusion height the laminates in an un-bonded tool would fail thus indicating a design limit. This was not to be the case, due to one further variable in the process which had previously been unnoticed up to this point. This was the variability caused through a laminates location in respect to the inlet gate.

To overcome this, a third experiment was designed and outlined in Chapter Nine. By setting all the laminate protrusions in the test-die to the same height the location variable would no longer influence the data. Six runs of ten castings were completed. The conclusion from this experiment was that no ingress occurred in an un-bonded laminate die where the laminates protrude 6mm or less, above their neighbouring laminates.

The study concludes through a discussion on the findings and their implications for the future of Laminate Tooling and pressure die-casting (Chapter 10), as well as the conclusions drawn (Chapter 11) and recommendations for further work (Chapter 12).

Chapter 2: Rapid Prototyping and Rapid Tooling

2.1 Introduction

Within the manufacturing context, there is a chain of events which result in the development and production of new parts and products. This process varies but, generally, has the same structure around the world. Figure 2.1 shows the traditional approach to this process.

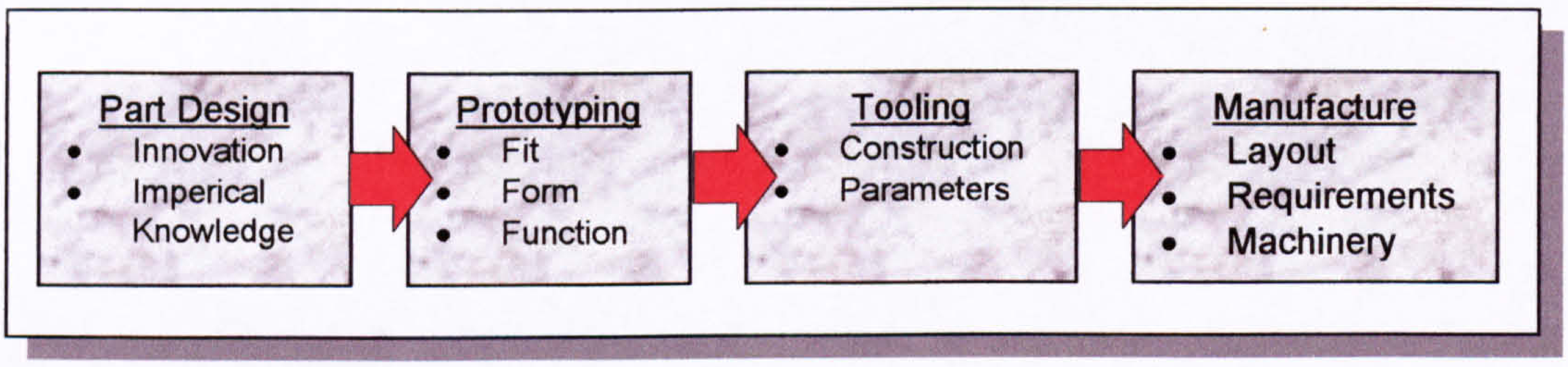


Figure 2.1 Traditional approach to product development

Though simplified, the schematic demonstrates how one function ends before another begins. In the traditional approach, part design must finish before prototyping begins. Likewise, prototyping must end before tooling begins. Within the context of modern manufacturing environment this process is flawed, mainly because each discipline must wait for its predecessor to complete its role. The consequence of this approach is that the design process is often completed without consultation with the tooling and manufacturing functions on issues relating to the implications of a new design or the optimal use of their resources.

The modern consumer requires products faster, cheaper and better than ever before. Terms such as 'Right-First-Time', 'Time-to-Market' and 'Quality Circles' have entered the manufacturing vocabulary and all symbolise how the traditional development process has been modified. Figure 2.2, below, demonstrates this concept.

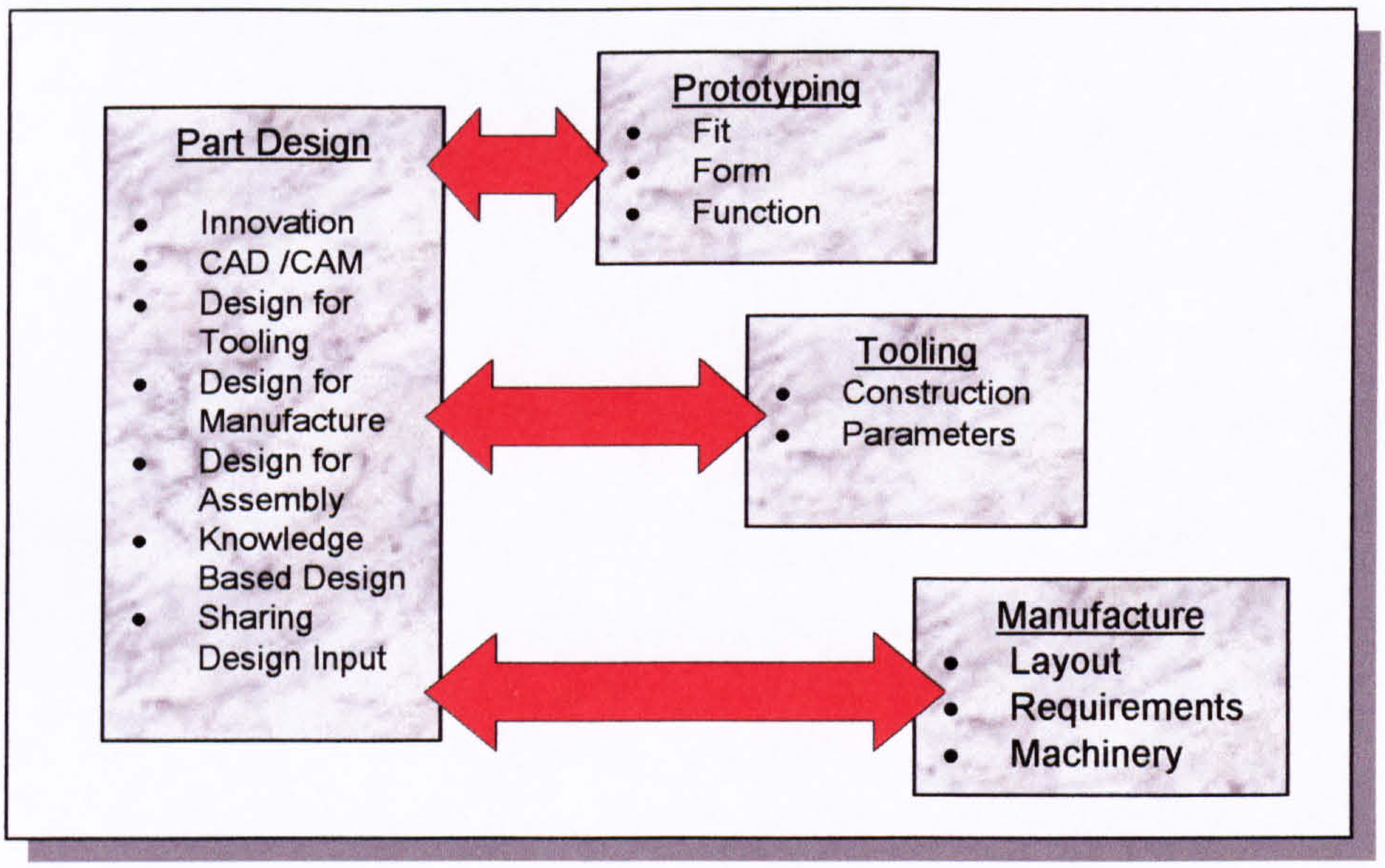


Figure 2.2 Concurrent approach from design to manufacture

Sharing the design stages with all those involved in the manufacture of the product compresses the time taken from initial concept to finished product. This approach has been termed Concurrent Engineering or Simultaneous Engineering and likewise those technologies that 'enable' Concurrency are termed Time Compression Technologies (TCT). The last two decades have seen an explosion of technologies, primarily centred around the computer, which have allowed Information Technology companies, such as Hewlett Packard, to generate hundreds of new products a year with any one product having a life cycle of no greater than a few months (Wohlers 1998). In Figure 2.2 it should be noted that the role of design has increased dramatically. The technologies specific to the design process are Computer Aided Design (CAD) and Computer Aided Manufacture (CAM) and represent those technologies that speed up the design process through the sharing of design data with the other manufacturing functions. The technologies specific to the prototyping process are classified as Rapid Prototyping. Those for the tooling process are called Rapid Tooling and for the manufacturing process are, currently, Computer Numerical Control (CNC) and Direct Numerical Control (DNC). None of these groups stand alone but all link directly to the each other through the sharing of data and information relating to a specific product and its manufacture.

The simplest way to place these technologies into context is to consider the computer as encroaching into the entire product development process, starting with the design function (with CAD-CAM), and gradually working through prototyping, tooling and ultimately to the manufacturing function as shown in Figure 2.3.

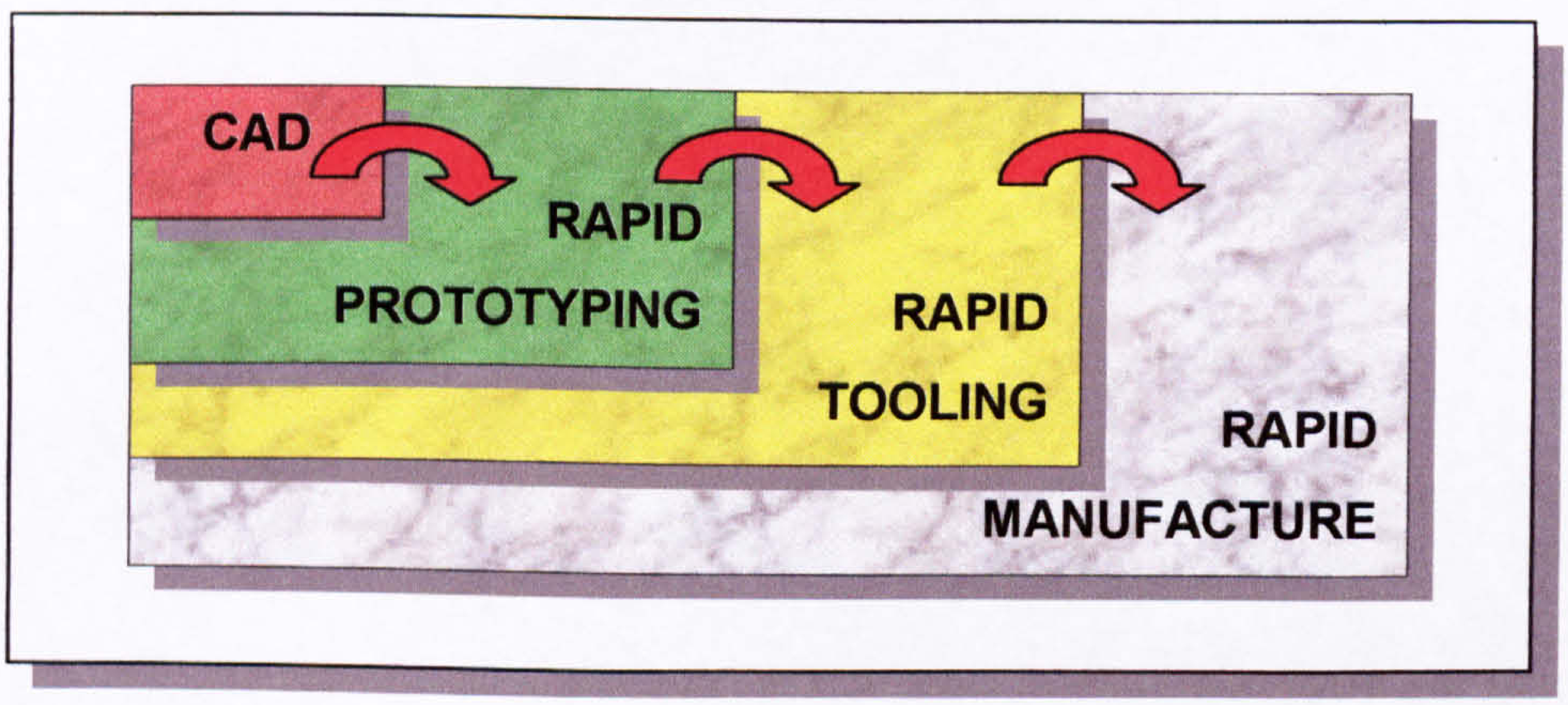


Figure 2.3 Progression of TCT's through design to manufacture

To fully understand the evolution of any of these concepts it is essential to understand the underlying technology i.e. Computer Aided Design.

2.2 Computer Aided Design

Computers, and specifically Computer Aided Design (CAD), are the 'enablers' for Rapid Prototyping and Rapid Tooling. The key to the implementation of this objective, and to ultimately reduce the time taken to develop and manufacture new products, is to ensure that information is shared at the initial design stage with all the manufacturing functions. In the case of part design it is essential that designs undergo as many iterations as possible before the 'design freeze'. This gives those who have to produce the design the opportunity to appraise it from their own perspective.

Two-dimensional (2D) drawings are the traditional method for representing a design but can be difficult to interpret by those who are not trained in technical drawing. Traditionally, the time taken to conceive and draft a design was restrictive and was a contributing factor as to why designers tended to work on their own before the design was passed on to the next stage (normally prototyping). This method is commonly referred to as an 'over the wall' mentality, in that each function works in isolation before 'discarding' the design over to the next function.

To overcome this attitude, and implement a 'Concurrent' approach to product development, companies required a method by which a design of a part could undergo multiple design iterations, in the minimum time, without having to repeat the arduous task of re-drafting the original design and its modifications. CAD technologies can be divided into four discrete categories:

- 2D CAD
- 3D Wireframe
- Surface Modelling
- Solid Modelling

As new CAD systems are developed they tend to incorporate elements of their predecessors and this describes the way in which the technology has evolved.

2.2.1 2D CAD

The first CAD systems were a natural extension of the drafting process. Designs of parts and products were generated as lines on a computer monitor, instead of on paper. The early systems were quite cumbersome and required the operator to undertake extensive training to use them.

The benefits of 2D CAD were somewhat limited but did allow the operator to make extensive modifications to a drawing without having to re-draft the entire plan, as was necessary in traditional drafting. Once the part had been defined as geometric data, it could then be scaled, added to, subtracted from and printed.

2.2.2 3D Wireframe CAD

3D Wireframe CAD was a major leap forward in the time it took to represent a three-dimensional (3D) part on a 2D monitor. 2D drawings had been the standard for communicating technical data for generations. Historically, constructing 3D objects on 2D planes required the designer to draft in three perspectives to represent the three views necessary to visualise that part. As computational power increased, it became possible to represent all three perspectives as a single three-dimensional object. As the name suggests, wireframe representations are a series of connected lines which represent a 3D object.

The system worked well for example, if the part being defined was a cube as each 'wire' represents an edge of the cube. Where curved sections to a part were defined it was sometimes difficult to visualise that surface on a monitor. Even so, a 3D Wireframe representation of a part provides much more visual information over a 2D representation when it comes to sharing the design concept with un-trained designers. Even today, most designers will construct parts as wirefames before converting them to the more realistic Surface or Solid models for visualisation.

2.2.3 Surface Modelling

Surface Modelling extends the abilities of Wireframe CAD by mathematically 'stretching' a surface over the Wireframe model, and automatically makes an excellent 3D-visualisation tool. Though surface models appear as solid objects on the monitor, they are in fact hollow shells encasing the model with zero thickness. More importantly, Surface Modelling allows complex curved surfaces to be generated, rendered and illuminated to give the impression of a solid object.

The automotive industry and Virtual Reality technologies, for example, make extensive use of Surface Modelling when visualising complex parts or 'virtual worlds' due to the savings in computational power requirements when compared to representing the data as a full Solid Model.

2.2.4 Solid Modelling

With Solid Modelling, a true solid object is defined. Xue (1996) describes Solid Modelling as *"the unambiguous and informationally complete mathematical representation of the shape of a physical object"*.

The technology uses two types of data to describe the model- geometric data and topological data. Geometric data describes the shape-defining parameters whilst topological data describes the connectivity between those geometric components. Modelling is achieved by taking a basic solid (such as a cube or sphere) and shaping it by subtracting or adding it to other solid geometric shapes to form a required geometry. Complex solids are achieved by extruding and rotating 2D geometric shapes to form a 3D object.

What separates Surface and Solid Modelling is that Surface Models contain no topological data. Surface models allow the construction of very complex surfaces through the use of non-uniform rational B-splines (NURBS). However, they suffer where individual surfaces fail to meet exactly, which may not be important for visualisation purposes but is critical for the technologies discussed later in this chapter. Surface Modelling also lacks the capability to describe the interior of an object, i.e. which side of the surface is solid (inside the object) and which is not (outside the object). Solid Modelling has this capability as well as the ability to describe material properties, physical properties, behaviour, density, inertia etc. used to define physical objects.

Solid Modelling only describes one generic group of CAD technologies and these are constantly being up-dated. Many packages now contain the benefits of both Surface and Solid Modelling such as Parametric and Hybrid CAD. These tools are also being extended to include previous design knowledge as in Knowledge Based CAD or Feature Based Modelling. CAD technologies have had a direct impact on the development of Rapid Prototyping and Rapid Tooling.

2.3 Rapid Prototyping

One of the outstanding obstacles in the move towards Time Compression is the need to reduce the time taken to produce a prototype. The importance of a physical model, or prototype, is often underestimated. Burns (1991) identifies six important reasons why a prototype is produced:

- **Concept-** to aid in the sharing of an idea to all those involved in its creation.
- **Fit-** to test the dimensions on the design so that it can be assembled with other components.
- **Form-** to assess the aesthetics and ergonomics of the part with users and the design group.
- **Function-** allows the part to be tested in its working environment within the limitations of the material it has been produced from.
- **Bid Requests-** allows sub-contractors to assess the product more fully from their supply standpoint
- **Marketing-** a powerful tool when communicating a design to a non-design based consumer.

Wohlers (1998) observes that *"while the developers of CAD systems have created impressive design aids, these aids are no substitute for the tactile and visual feedback provided by touching and studying a physical model"*. For Time Compression to be effective the production of prototypes had to be addressed.

With the early CAD systems, the draftsman would generate a design and then print those designs onto paper. These plans would then go through the lengthy process of being hand crafted into a physical representation of the part. The process was lengthy and required great and skill became a severe bottleneck in the product development process.

If a 3D part could be represented as digital data, then it was a logical step to use that data to control a machine directly to produce a physical prototype. During the 1980's researchers began to explore the concept of building parts by adding layers of material. Hamilton (1990) observes that pattern makers have been using layers of wood to build prototypes for many years. It is this approach which is now known as Rapid Prototyping

2.3.1 Definitions

For this thesis the term Rapid Prototyping (RP) will be used to refer to all those technologies which, as Burns (1993) states, *"Automate the process for fabricating 3-dimensional, solid objects with raw materials"*. Mieritz (1993) goes further in describing Rapid Prototyping as *"A group of technologies which make it possible to produce models and prototypes of complicated parts directly from 3D CAD. The objects may be produced in different materials depending on equipment, without using tools or fixtures"*.

Rapid Prototyping is the term most commonly used in Europe to describe these technologies. As with many technologies developed simultaneously around the globe, different names become assigned to, essentially, the same process. In fact, during the early stages of development there were many discussions as to what this technology should be called and to this day there are still certain camps which prefer one title to another. In the United States they commonly use the terms Freeform Fabrication (F^3), Desktop Manufacturing, Solid Freeform Fabrication (S.F.F.), Layered Fabrication, Automated Fabrication or Tool-less Manufacturing (depending to whom you speak).

Burns (1991) describes Rapid Prototyping as an 'additive' process, as opposed to 'subtractive' or 'formative', which is how almost all conventional machining operations can be described. As the name 'subtractive' suggests, most machining operations rely on taking a block or billet of raw material and cutting, milling or grinding it to produce the required part. Casting and injection moulding are 'formative' processes. The 'additive' process involves taking a material and selectively adding successive material in a layer by layer approach until the part is finished.

The key to understanding RP is in the statement 'layer by layer'. A good analysis is producing a house. There are two ways to go about it, you can either carve from solid rock as in a cave (analogous to machining from solid stock) or you can build it layer by layer with bricks (this is RP). Brick built houses can contain an infinite variety of enclosed spaces and complex internal features. When a part is carved from a solid block there are limitations with the tool head which restrict access into the part to form complex internal features. By building a part in layers and bonding each one to the layer below, each 2D layer can include as many complex internal features as required with seemingly impossible detail.

2.3.2 CAD and Rapid Prototyping

The development of both CAD and Rapid Prototyping has been a close partnership with the development of Rapid Prototyping being driven through evolution of CAD. The development of Rapid Prototyping will be covered in detail in the following section but it is worth considering how the evolution of CAD has driven it.

In 1988, the Albert Consulting Group created a defacto standard for slicing CAD models called .STL (stereolithography language). There are three steps to this procedure:

- Selecting the part which is to be converted to .STL format.
- Setting the tolerance parameters for the process.
- Creating a triangular representation of the geometry into an output file for slicing.

As Miller (1994[1]) explains, the process of triangulation is called 'tessellation'. This, essentially, covers the surface of the model with a triangular mesh. Each triangle is defined by several sets of x, y, z, co-ordinates of the triangular vertices, as well as the corresponding normal vector. With the .STL format, the triangles must follow the 'vertex to vertex' rule whereby all triangles must meet all adjacent triangles along a common edge.

The .STL format prepares the CAD model by identifying which way the surface elements face, also known as surface normals, and how they relate to each other. With Surface Modelling, tessellation is quite an arduous process as the operator must manually check the model prior to tessellation for un-enclosed boundaries and Möbius strips, to ensure the production of fully enclosed (watertight) surfaces.

Adjacency Tolerance (how close two surface boundaries are before they are considered united) must continually be checked with Surface Modelling as must Auto Normal Generation (direction from the surface of a triangle which is solid) whereas the process of Solid Modelling automatically defines these parameters. Miller (1994[1]) advises any company going into RP of having a minimum specification of Solid CAD.

Within RP, there is no single all encompassing process. As the field has developed, so has its diversity. Prototype parts are required for various different reasons and this has resulted in many novel and different approaches.

2.3.4 Stereolithography (SL)

There has always been some debate as to the exact beginnings of Rapid Prototyping. Even though the first patent for this technology was awarded to Kodama (1981) in Japan, it is generally accredited to Charles Hull (1994) of 3D Systems in the U.S. who launched the world's first RP machine onto the market in December 1987.

The underlying discovery which spawned Stereolithography was that certain polymers will undergo a 'phase change', or conversion from liquid to solid, under the influence of certain wavelengths of light or radiation. DuPont made this discovery over 40 years ago. The first investigations into the potential of these materials were by Magnus (1965), who was looking at using the 'phase change' in certain polymers and metals to produce solids, and Swainson (1971) who saw interesting results with the selective polymerisation of materials exposed to ultraviolet (UV) radiation. They explored techniques whereby UV light would be shone into a vat of photopolymer using more than one source of light. Where UV light beams crossed a peak intensity would cure the polymer at that point. 3D forms were created by using two lasers crossing inside the vat or a system where two masks would be used in opposing planes to define the object within. Both had the fundamental flaw of not being able to support the object in the vat or control the defracted light as it entered the liquid. The breakthrough came when one UV laser was used to scan just one layer of photopolymer at a time instead of the whole 3D object. Building the prototype as discrete slices was the key and a laser can polymerise a point of resin (voxel) without defraction as long as it is on or near the point where the beam enters the vat (i.e. the surface).

Hull made this breakthrough by using a UV laser to scan each 2D profile onto the surface of a vat of photopolymer resin. Figure 2.4 is a schematic of this process.

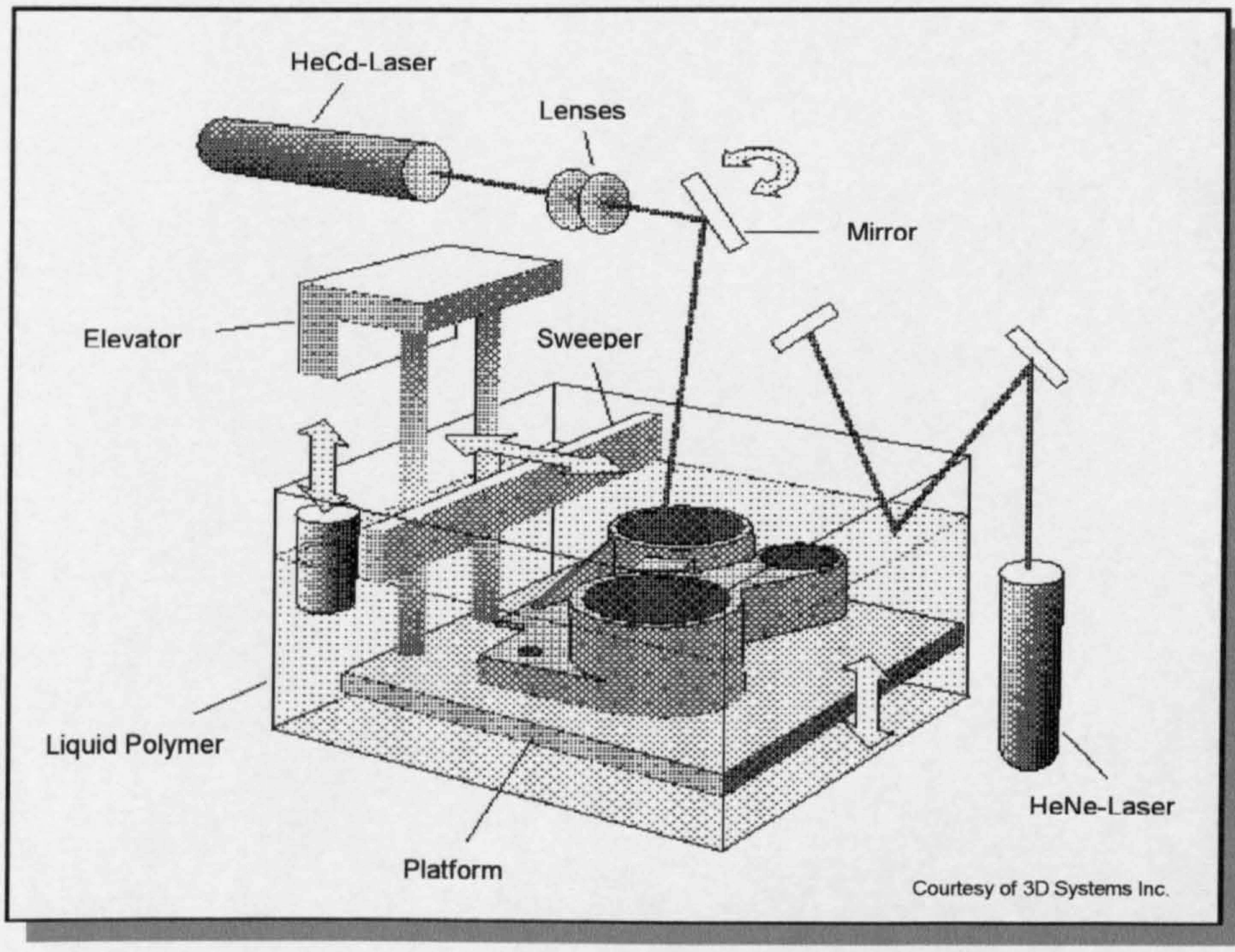


Figure 2.4 Schematic of the Photocure Process

Where the laser strikes the surface of the resin it solidifies. Solidified material is prevented from falling to the bottom of the resin vat by a platform lying just beneath the surface of the resin. By feeding the sliced 2D data from a CAD model the laser scans the solid section of that slice onto the surface of the resin. The platform holds this layer, descends by the thickness of each pre-defined 2D slice and then scans the next slice. Each layer is bonded to the layer below by ensuring that there is an overlap in the penetration of the laser beam into the resin vat from one successive layer to the next.

This process is repeated over a period of hours until the part is complete. On completion, the part is lifted from the vat, solvent washed and cured in a UV oven. Hull named this process Stereolithography (SLA) and the first commercial system (SLA-1) was introduced by 3D Systems in 1987.

3D System's SLA process has been through many iterations with improvements being added to each new machine from the SLA250, 350 and 500 (which denoted the volume in millimetres cubed of the resin vat) to the recent addition of the SLA 7000 series. Xue (1996) identifies the limitations of the process as being:

- Support structures must be built onto the desired part where overhangs occur. Without them the uncured part would tend to sag in the resin vat.
- Each layer thickness is defined by laser penetration in the resin vat and the amount that can be re-coated safely. This currently ranges from 0.75mm down to 0.025mm depending on the level of detail required in the part.
- Where excess material and support structure is removed from the part then re-cycling is not possible. Re-using resin from one job to the next leads to its eventual degradation.
- There are health and safety issues when handling the photopolymer.

Other commercial systems currently based on this technology are shown in Table 2.1:

Aaroflex	Stereolithography (SL)
NTT Data / CMET	Solid Object UV Plotter (SOUP)
Sony / DMEC	Stereolithography (SL)
Denken	Solid State Stereolithography
Meiko	Stereolithography (SL)
Fockele & Schwarze	Stereolithography (SL)
Cubital	Solid Ground Curing (SGC)

Table 2.1 Stereolithography Producers

From Table 2.1, one process which stands out for its innovative approach to stereolithography is Cubital's Solid Ground Curing (SGC) system. SGC uses laser photocopier technology to generate a UV mask which represents a negative image of each 2D slice. A UV lamp is shone through the mask to selectively polymerise the top layer of resin.

What sets this technology apart is that as each layer is hardened the excess liquid photopolymer is sucked off and replaced by wax that acts as a support structure. Where more than one part is to be built in the vat it is not necessary to begin building all of them simultaneously. Parts can be built after one part is finished within the same build volume. The process has more stages than SLA, including a milling stage, and is excellent where high throughput is required.

To date, Wohlers (1998) identifies 20 manufacturers producing one or more RP technologies. Only eight of these commercial processes are based on SLA. The variety of processes now available has increased significantly as has the number of materials that can be considered (polymers, metals and ceramics) in a variety of base states (liquids, powders, sheets). Figure 2.5 shows how Kellock (1997) distinguishes each of these different RP techniques. He defines each under three categories under the heading of 'material addition'. This term relates directly to Burns' 'additive' processes.

Of these different classifications, there are fundamentally four further processes that dominate the market:

- Selective Laser Sintering (SLS)
- Laminated Object Modelling (LOM)
- Fused Deposition Modelling (FDM)
- Jetting

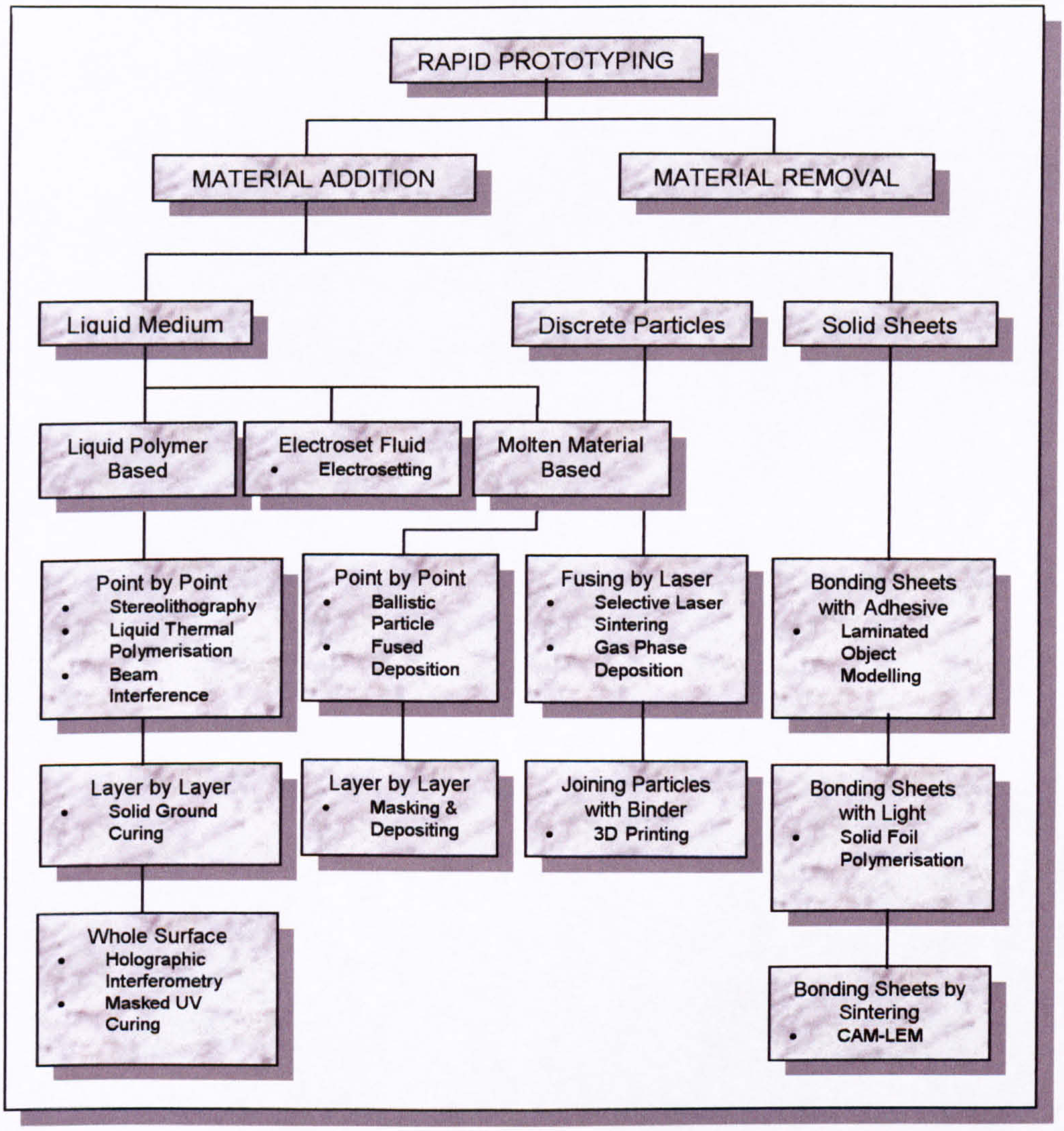


Figure 2.5 Kellock's breakdown of the RP processes

2.3.5 Selective Laser Sintering (SLS)

Developed by Carl Deckard and Professor Joe Beaman at the University of Austin Texas in 1986 and commercialised by the DTM Corp. in Austin, Texas this process was not available in Europe until 1993. The process is a layer by layer approach but, in this case, a polymer powder is partially fused using a high powered laser. Dickens (1995) explains that the sintering process does not fully melt the powder but allows molten material to bridge or 'neck' between particles. The build chamber is also heated to just below the melting point of the raw material, which reduces the energy required by the laser to sinter the powders together.

The first layer (around 0.1mm) of powder is deposited onto a Z-controlled platform. A laser scans each 2D profile of the model onto the powder which selectively sinters the powder. This process is repeated for all consecutive layers. On completion, any loose (un-sintered) powder in shaken off to reveal the model.

The key advantages to this process are that no support structures are required on the part, as the un-sintered powder provides adequate support. The process produces robust parts from standard production polymers ABS and polycarbonates (Marcus *et al* 1993).

Figure 2.6 and 2.7 show the process and parts assembled elements for physical testing.

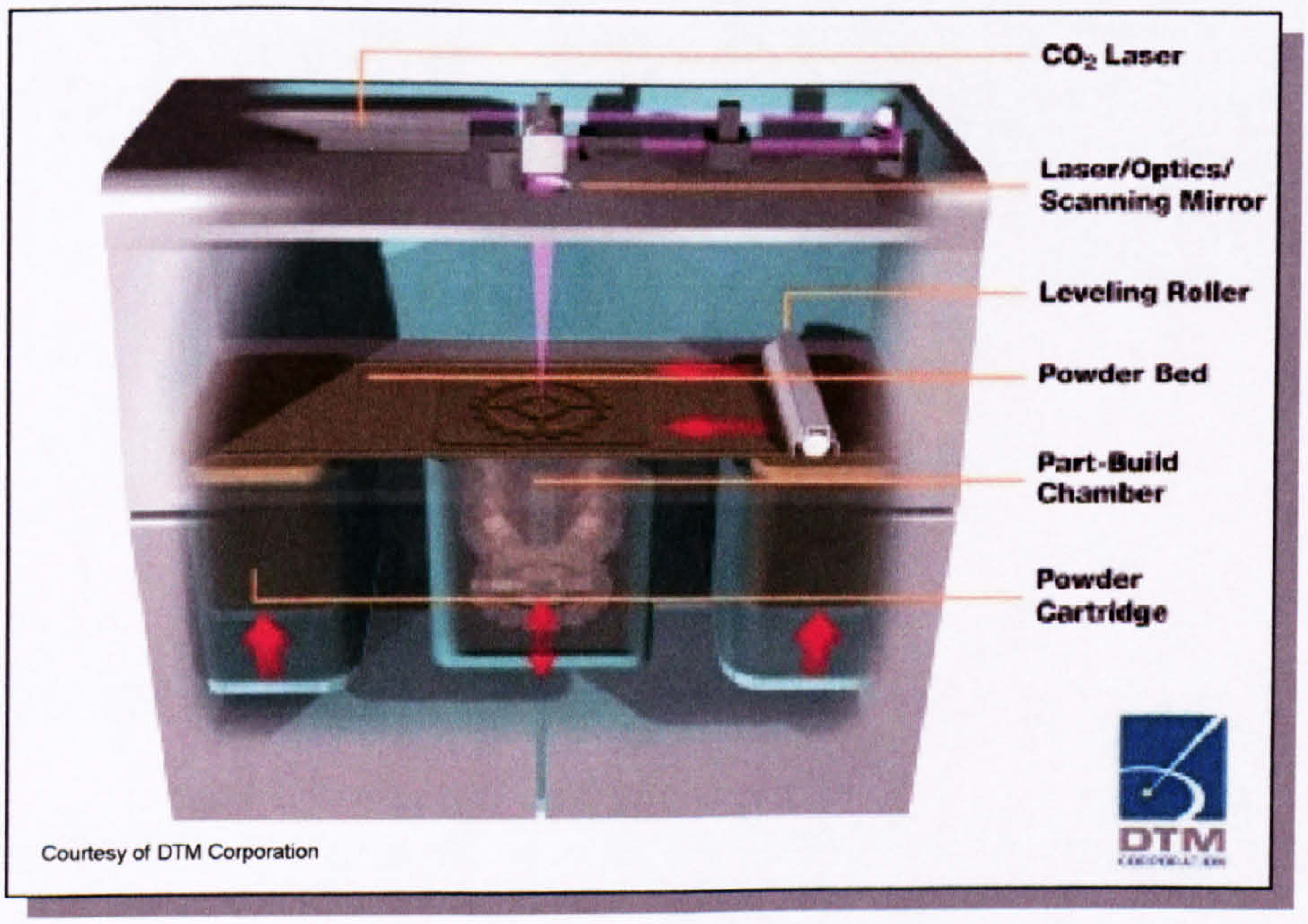


Figure 2.6 Selective Laser Sintering (SLS)

Figure 2.7 Prototype parts assembled with working elements

One further advantage of the system is that there is little waste, compared to SLA, as the powder can be re-used and there are fewer health and safety issues. Limitations of this process include:

- The surface finish tends to be relatively coarse compared to SLA models.
- Time is required to cool down parts without distorting them.
- The build size is restricted to the size of the powder chamber.

2.3.6 Laminated Object Modelling (LOM)

Laminated Object Modelling followed closely behind SLA, with the first patent being issued in 1987. Helysis Inc commercialised the process and launched their first machine in 1991.

Miller (1994[2]) states that in this process, layers of adhesive backed foil (paper, plastic, or currently ceramic) are stacked, layer by layer, and heat bonded to one another. As each layer is pressed and heated in place, the 2D profile is cut with a laser. Upon completion, the excess paper is broken off the model to reveal the part in the material.

Where paper is used, the appearance of the parts are similar to that of wood, which was one reason why pattern makers like the process. No support structure is needed but removal of the part from the surrounding material can be arduous and cause problems with enclosed volumes. Figure 2.8 describes the working elements of the machine and Figure 2.9 shows the process of part removal.

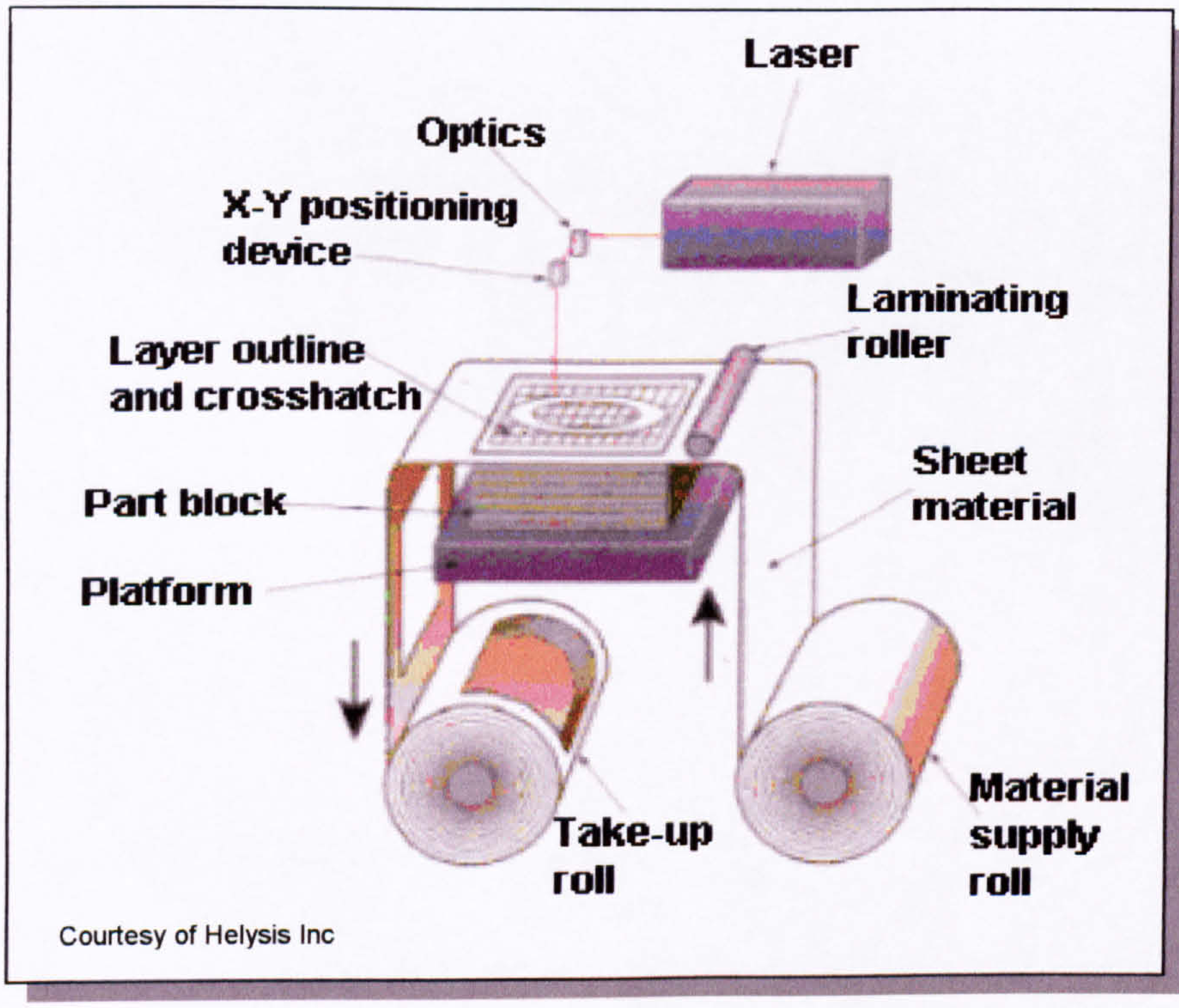


Figure 2.8 Working elements of LOM process

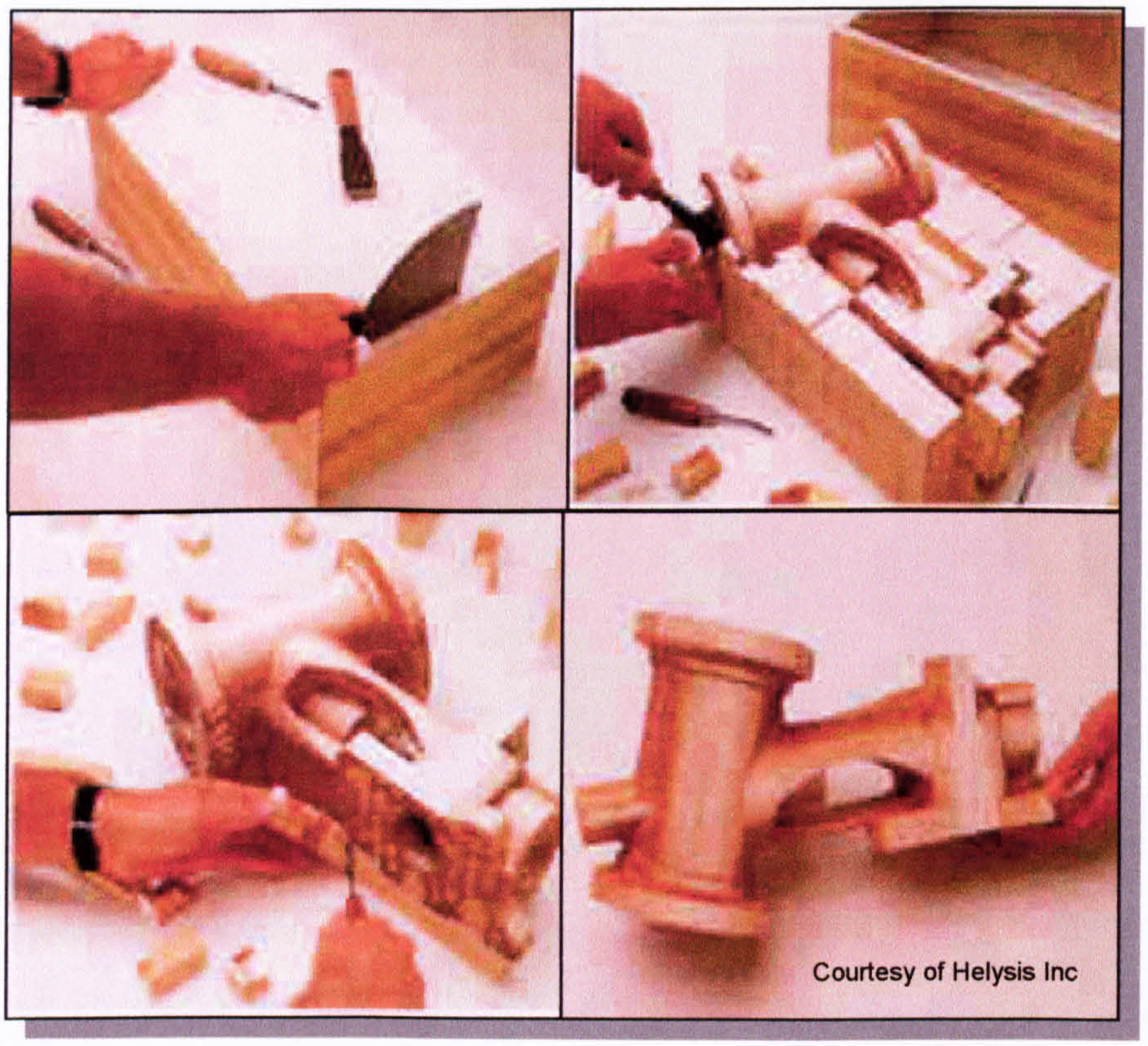


Figure 2.9 Fours stages of part removal

The process is fast and scaleable, compared to SLA and SLS, but has its limitations:

- Parts are susceptible to moisture ingress which can lead to distortion.
- Parts can only be used for aesthetic appraisal and patterns, not functional testing.
- Parts often need secondary surface preparation to simulate plastic parts.
- There is a fire risk.

2.3.7 Fused Deposition Modelling (FDM)

Developed by Scott Crump in 1988, the first machines were commercialised and installed in 1991 by Stratasys Inc, (Miller 1994[2]). The principal is similar to squeezing a tube of toothpaste, in that molten material is extruded through a fine nozzle that moves continuously to build a part. Almost any material can be extruded with a relatively low melting point such as thermoplastics and casting waxes. Figure 2.10 and 2.11 show the Stratasys machine as well as some typical parts.

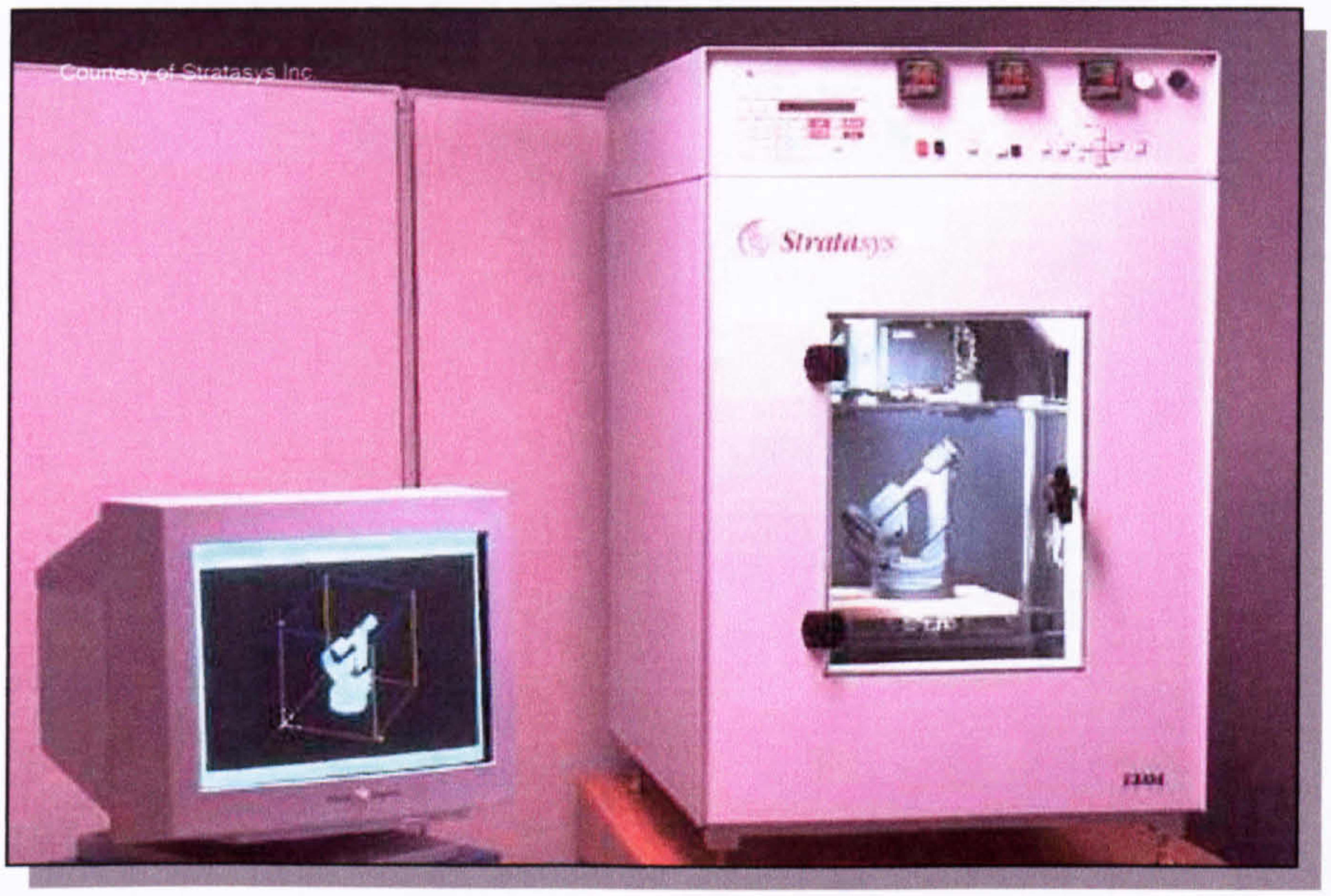


Figure 2.10 Fused Deposition Modelling

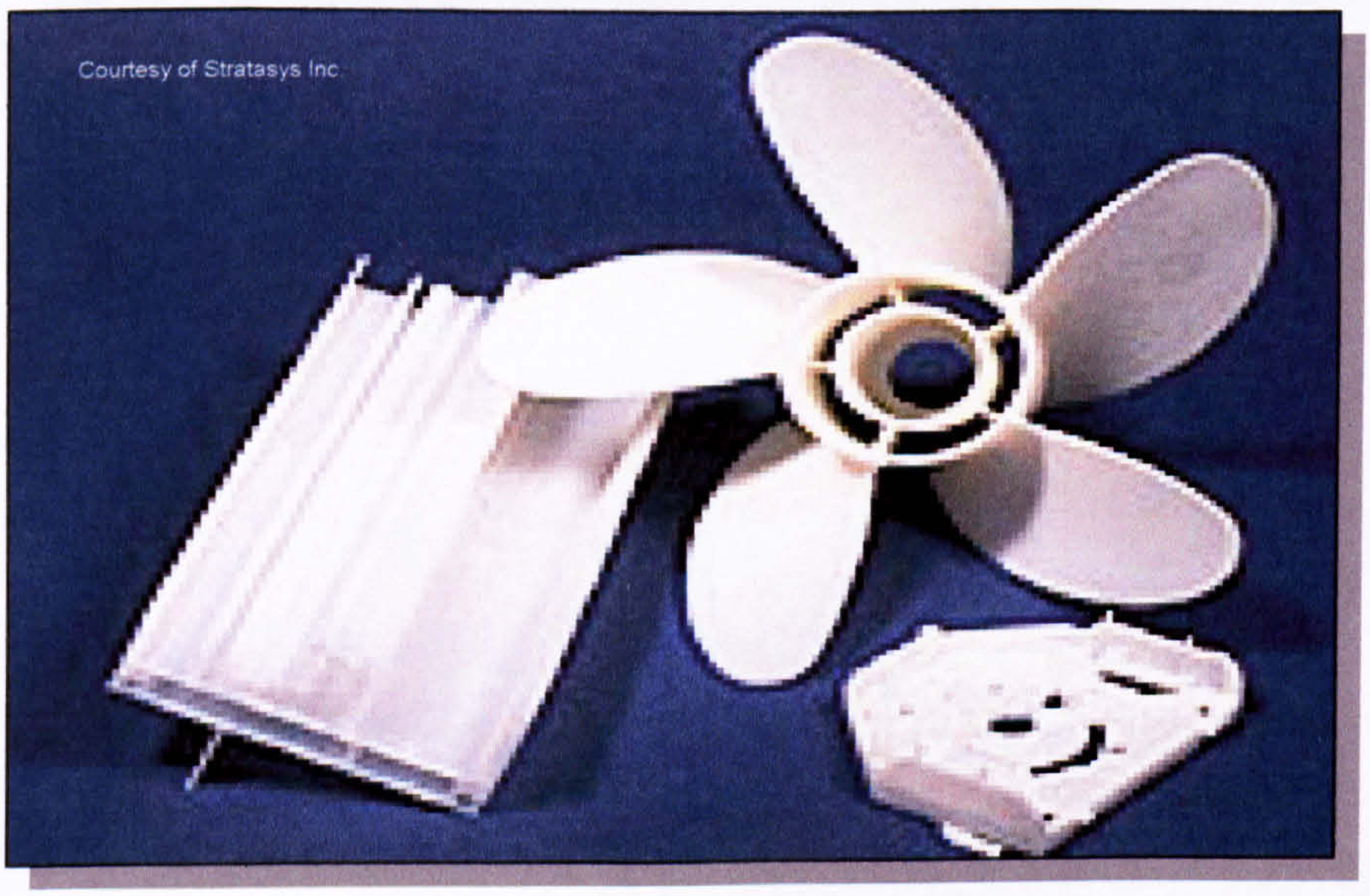


Figure2.11 Typical parts generated by FDM

FDM is currently one of the cheapest methods to produce prototype parts and, apart from the support structure, there is little wastage of raw material. These prototypes are robust and can then be used, in some cases, for physical testing of components. Limitations include:

- Relatively poor finish to the surface of parts.
- Possible distortion as the parts cool.
- An extensive support structure as parts will sag where overhangs occur.
- Over application of polymer on the part affecting appearance and finish.

2.3.8 Jetting

It has often been believed that a truly flexible prototyping tool would be one which could work on the desktop beside the CAD workstation (Throup, 1996). This concept has been dubbed 'desktop manufacture' and is a major step towards what can only be described as '3D printing'. There now exists a range of processes in this 'niche' market that fit this criteria and all are loosely based on the concept of the inkjet printer head that deposits waxes or polymers instead of ink.

In 1996, 3D Systems launched the Actua 2100 and the name they applied was Multi-Jet Manufacture (MJM). The system deposits droplets of wax-like polymer, layer by layer, onto a descending platform. Figure 2.12 shows a schematic of the working elements of the process.

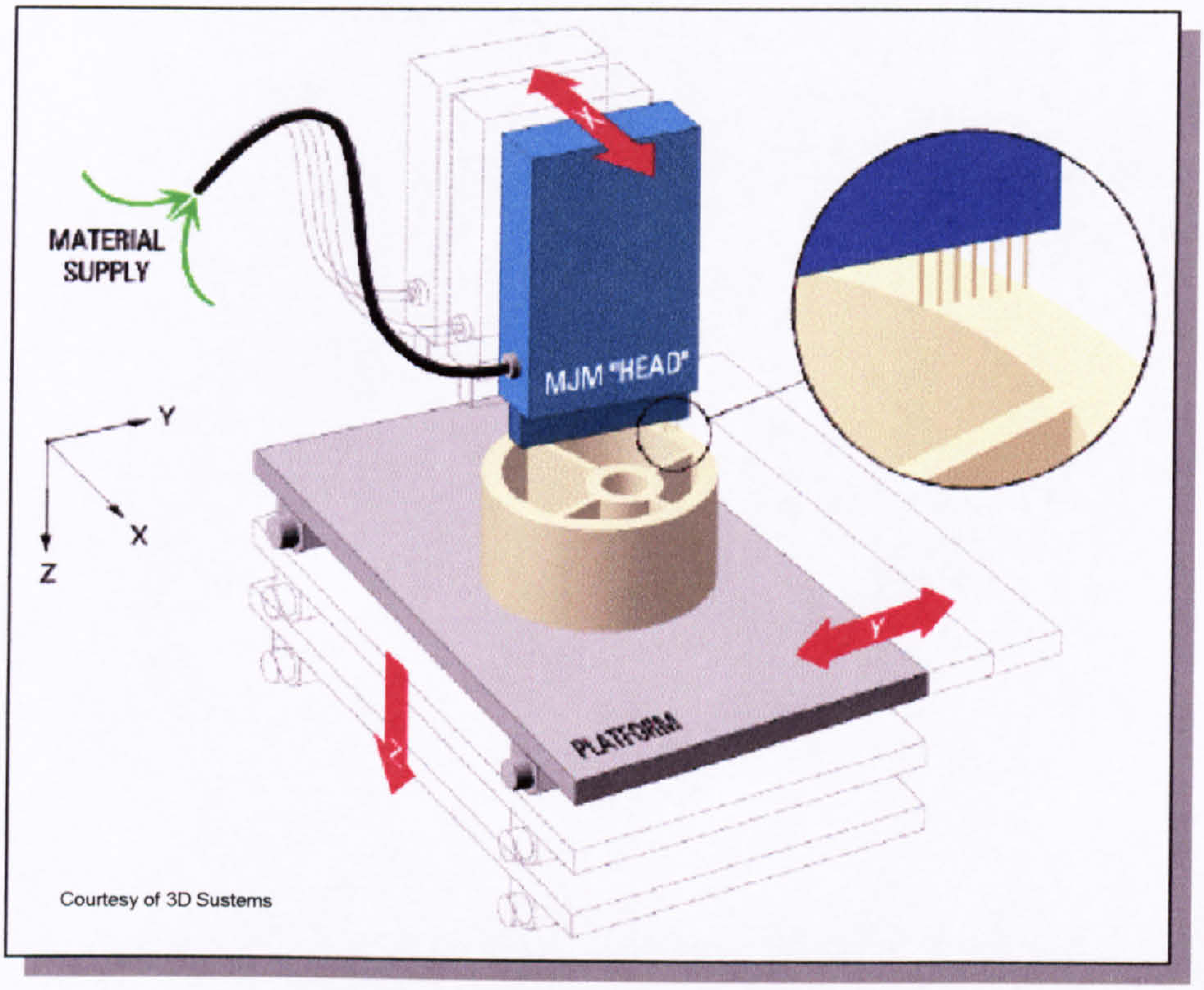


Figure 2.12 Working elements of the Actua 2100

First patented in 1984, (Dickens 1995), there is more than one version of this system currently on the market. 3D System's have also launched the Thermojet which has 96 peizo jets working simultaneously to build the wax prototype.

A similar technology, called ModelMaker, was launched in 1994 by Sanders Prototype Inc. The process also uses inkjets but fills a niche in the market where incredibly fine detail is required. Sander's parts are designed to be small and very intricate and being wax they are commonly used as wax patterns for investment or centrifugal casting (e.g. Jewellery). Figure 2.13 shows the level of detail possible.

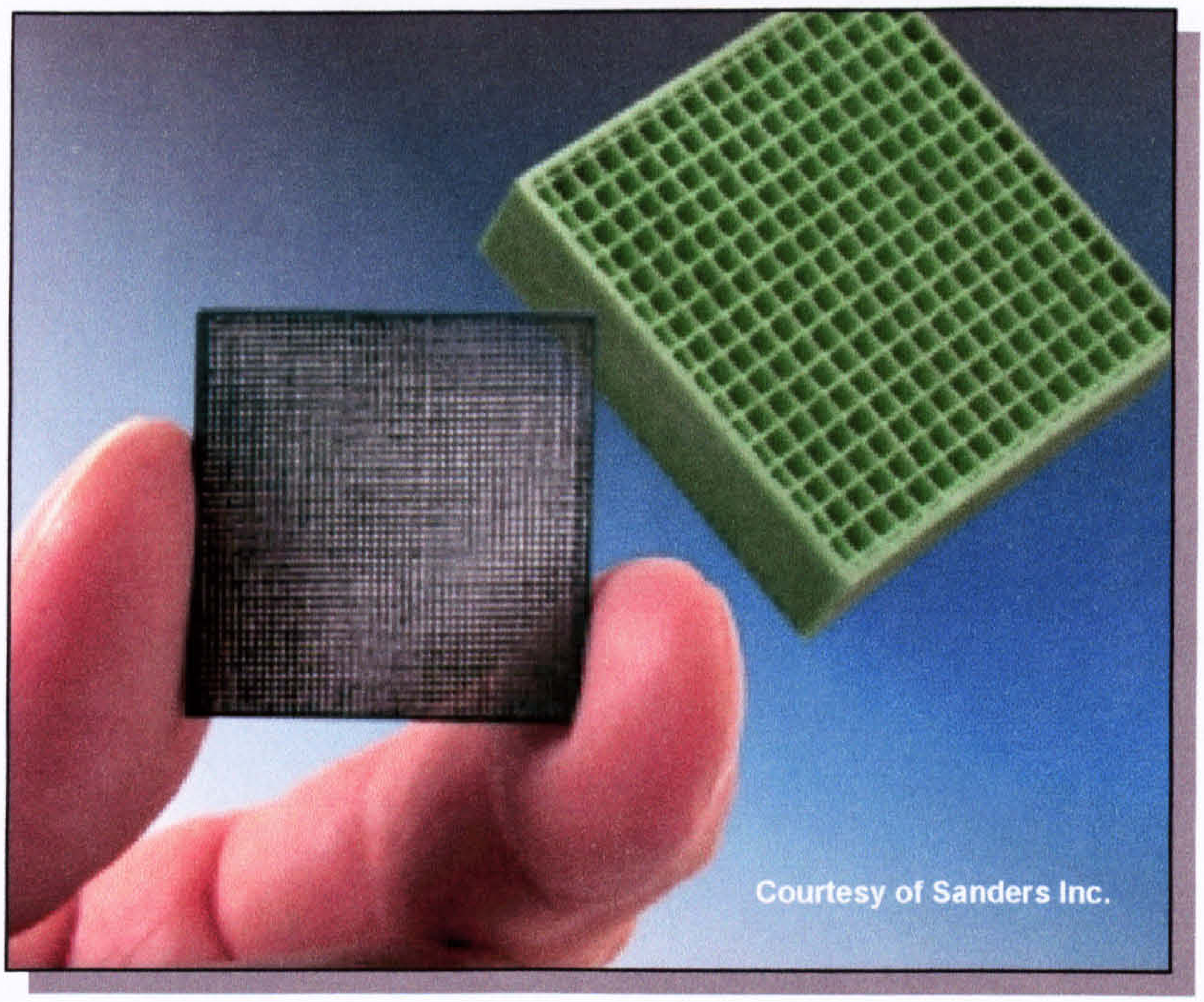


Figure 2.11 Sanders ModelMaker

The final process in this group was developed by Professors Emmanuel Sachs and Michael Cima in the 1980's. The process is called 3D-Printing (3DP) and has been studiously developed with the first licences being awarded to Soligen Inc., Z-Corp and Extrude Hone. The Z402 by Z-Corp is a long awaited and much publicised product which differs from other jetting technologies in that the inkjets deposit a binder onto a layer of powder. In many ways, the process is a fusion of SLS and Jetting giving the benefits of both. This is the first desktop system which allows materials other than waxes to be built quickly. Using a secondary sintering process almost any material can be converted into a functional prototype.

2.3.9 Current Status of RP

Wohlers (1998) observes that the sales of RP systems have been sluggish over the last year. This may be due to the market maturing and also competitive pressure between vendors. Either way, there has been a sharp decline (up to 50% for some vendors) in the prices asked for these systems.

In 1997 the world RP market grew 7.5% to a value of $452.6 million. During that year, 1,070 RP machines were sold world-wide which was the first year that sales had exceeded 1,000 units (this was up from 787 units in 1996). To put this figure into perspective, since the launch of the first SLA-1 in 1988, total world sales have been 3,289 units. Forecast unit sales for 1999 are expected to increase to 1,875.

3D Systems, alone, controlled 20% of all sales world-wide in 1997 and dominance was only once exceeded in 1996 when Stratasys sold 257 units to 3D's 175 units. 3D now stand to retain this position with the launch of the Actua and the improved Thermojet, but it will be interesting to see how the likes of Z-Corp will affect these sales in the near future. Wohlers (1998) shows the breakdown of the global market in Figure 2.14.

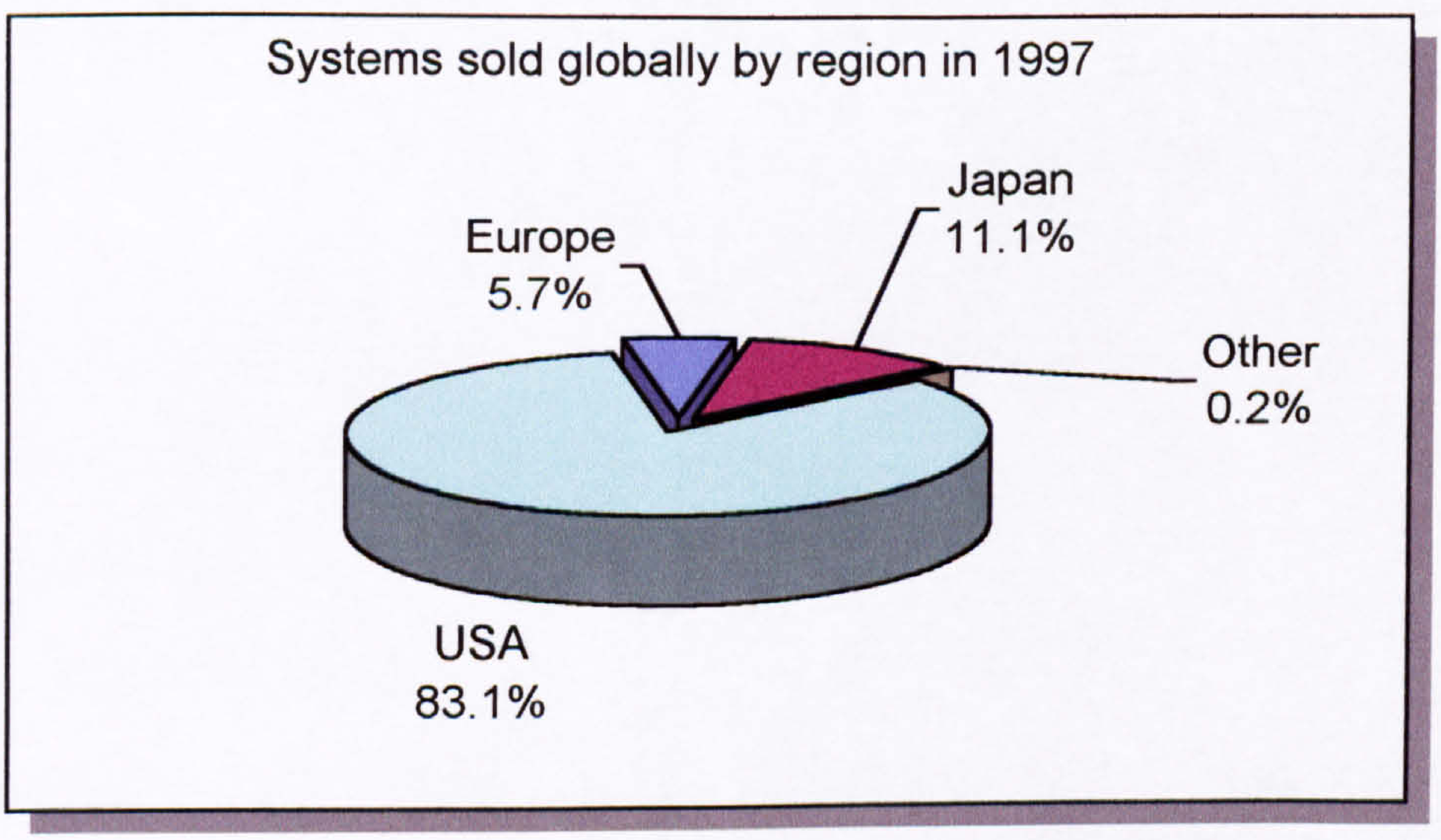


Figure 2.14 Percentage of market share by region

Wohlers also identifies two discrete market sectors within RP, these are products and services. Products include RP systems, upgrades, materials, software etc. and services include revenue generated from RP models through Service Bureau's, maintenance, training, and consultancy. This currently stands at \$194.6 million being generated, through product sales against \$258 million generated through services. Having said this, the service bureau dominance of the market declined rapidly in 1997 with only 3.1% growth as compared to 43.1% in 1996. This indicates a clear shift towards 'in-house' prototyping as well as a maturing of the industry.

2.4 Rapid Tooling (RT)

One of the delicate phases in the design process, particularly in Concurrent Engineering, is the point at which the design process ends and tooling begins. This is known as the 'design freeze' and at this point, no further changes are allowed to the design. Tromans and Wimpenny (1995) state that producing the tooling for a product is probably the single most expensive operation in the product development process. Traditionally, companies had only one chance to build the dies, moulds, press tools etc, necessary for a product and any mistakes made in the tool had to be lived with as the cost of correcting them was too high.

Burns (1991) states that at the beginning of the 1990's, manufacturers and technologists began to ask whether it was possible to apply RP techniques to the production of tooling. Gustafson *et al* (1995) saw this move as part of the more widespread decline in skills in the pattern making industry. Applying RP to tooling would bring down the cost of the tools, speed up the 'time to market' race, allow multiple iterations of a design and, for the first time, allow the production of 'Prototype Tooling' for short production runs. This concept quickly became known as Rapid Tooling (RT).

Rapid Tooling is the next logical progression of Time Compression Technologies into the manufacturing structure and is commonly viewed as an extension of RP. 3D-CAD data is used to construct either a robust pattern (in the construction of a mould) or is used to build a finished tool/mould in one step. By consensus, these two approaches have become known as 'Indirect' and 'Direct' Tooling. Adams *et al* (1998[2]) divides these two categories, further, into 'Soft' and 'Hard' tooling. Figure 2.15 shows the interrelationship of these four categories.

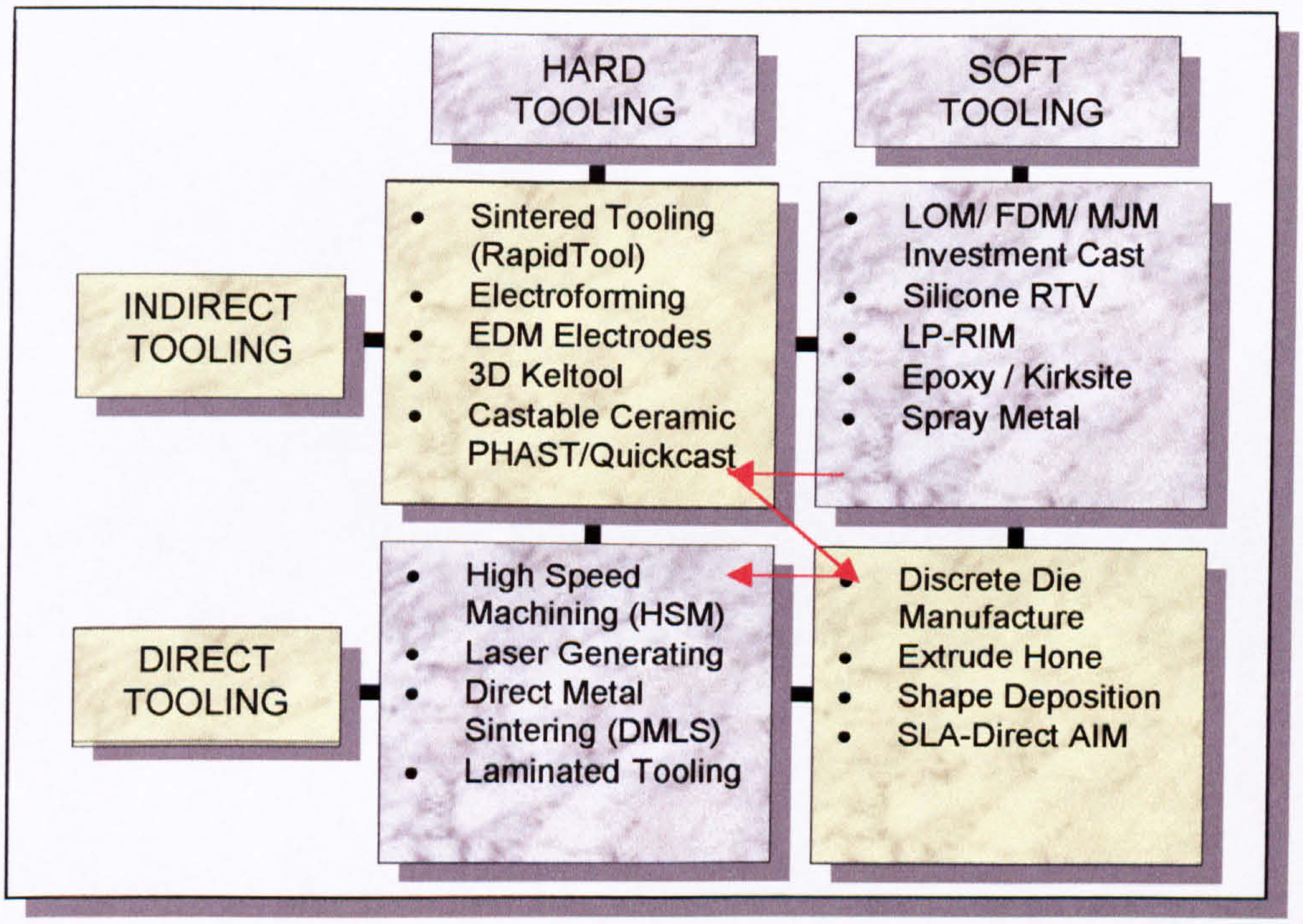


Figure 2.15 Adam's division of RT processes

By Adam's definition, there are four separate categories to the model, an explanation of which follows. The four categories are:

- Indirect Soft Tooling
- Indirect Hard Tooling
- Direct Soft Tooling

- Direct Hard tooling

2.4.1 Indirect Soft Tooling

Soft Tooling is characterised by the materials from which a tool is constructed and includes silicone, resins and polymers. These tools are not intended to produce tens of thousands of parts and are commonly used to mould prototype parts or be used for short production runs.

The first groups to venture into Rapid Tooling were keen to exploit their existing RP technologies. RP systems such as SLA, LOM, SLS and FDM produced good prototype parts but were, generally, not robust enough to build moulding tools. Their approach was to use an RP part as a 'master' or 'pattern', around which a robust mould could be formed. For example, where an RP part is too soft or brittle, a flexible mould can be cast around it using room-temperature-vulcanising (RTV) silicone. RTV tools can reproduce an RP pattern with incredible detail (it will reproduce fingerprints left on the pattern).

With the RP pattern removed, the RTV tool could be re-assembled and injected with a two part thermo-set resin. A second approach was to use an RP pattern to form an epoxy resin tool. A parting line is defined on the pattern and an aluminium filled epoxy resin is used to form one half of the tool around it. This is inverted and the second half of the tool is built off the parting plane of the first half of the tool. Release agents are critical to remove the pattern from the resin tool, as is location of the parting line. These tools are normally inserted into a bolster which allows mounting on a moulding machine.

Reproduction from the pattern is high, but fine up-stand detail within the cavity tends to be brittle and is prone to breakage during moulding. The system does allow copper pipes to be formed within the tool for cooling.

Kirksite Casting also comes under this category (Wohlers, 1998). It involves an RP master around which a flexible urethane mould is produced. Plaster is set inside the mould and it is around the plaster pattern that the Kirksite (zinc alloy) is formed to produce the tool. Kirksite is more robust than epoxy, but the trade off is the number of extra iterations (reverse geometries) which are required.

The final process under this category is Sprayed Metal Tooling. Adams and Wimpenny (1998[1]) observes that it is debatable whether this process is a Hard or Soft method as some of these tools have been used to produce many thousands of parts in production trials. Thermal Spraying is a mature technology which is used for cladding and refurbishing worn metal components. Segal & Cobb (1995) define the concept behind it is a jet of compressed gas fired through an area of molten metal.

A small pool of molten metal is produced either by feeding two consumable electrodes towards each other and striking an arc between them or simply heating the metal in a melt chamber within the gun. The molten metal is quickly entrained into the jet of gas and is projected towards an RP pattern. On impact, the particles impinge on each other to form a layer of deposited material.

To produce a tool using this process involves taking an RP pattern, defining a split line for the tool which will be produced from it, applying a release agent to the part and then spraying one side of the part with a 1-3mm deposit of sprayed metal. This can be zinc or zinc/aluminium alloy. The spray-metal shell is then backed with an aluminium filled epoxy resin to strengthen it. Once set, the first half of the tool is complete and is inverted to repeat the procedure for the second half of the tool.

The finished tool can be used for injection moulding and the whole process can be completed within 48 hours from receipt of an RP pattern. The process does have severe limitations where complex internal geometries are required which normally result in the inclusion of solid inserts into the tool. The process is very scaleable as shown in Figure 2.16.

Figure 2.16 Example of a Spray Metal tooling

2.4.2 Indirect Hard Tooling

Hard tooling refers to those Rapid Tooling methods which produce high throughput production tools. In Aerospace applications, this is 1,000 parts, and in Automotive applications is over 10,000 (Adams and Wimpenny, 1998[2]).

Indirect Hard Tooling consists of those efforts by existing RP vendors to produce moulds and tools capable of full and partial production runs. Their solutions are either to produce the tool on an existing RP machine and use a secondary finishing process (RapidTool, ProMetal, EOSINT-DMLS) or to construct the tool around an RP pattern (Keltool, PHAST, CEMCOM, Dynamic Tooling, ExpressTool)

DTM's Selective Laser Sintering-RapidTool process is a modification to the existing SLS process whereby polymer powders are sintered together to form a prototype part. RapidTool adds two further iterations to this process to form metal tooling. The laser used in the process is not capable of melting metal powders so, to overcome this, metal powders are coated with a polymer. The powder is called 'RapidSteel' and when scanned by the laser the polymer coating 'necks' to hold the particles together in a 'green' state. The part is removed from the machine and placed in a furnace where the polymer is burnt off and the metal powder sintered. During this process, the part is infiltrated with molten copper which is drawn into the porous structure through capillary action.

Subramanian *et al* (1995) comments that the process reproduces complex geometries and the tools can withstand injection-moulding conditions. The process is limited in its accuracy by the secondary processing of the part. Wohlers (1998) states that the newcomer into this field is Extrude Hone who have acquired the licence for the 3DP process. As with the Z-Corp system, the PROMETAL Rapid Tooling System uses inkjets to deposit a 'binder' onto metal powder to form the *green* part ready for firing and infiltration.

3D Systems entered this field with the acquisition of the Keltool process. Keltool moulds are produced by generating the core and cavity as an SLA pattern. Around these are formed a silicone rubber mould which, on removal of the RP pattern, are filled with a mixture of metal powder (A6 tool steel and tungsten) and binder. This is compacted into the mould and cured after which it is fired and infiltrated with molten copper in much the same way as RapidTool. The process is accurate with excellent reproduction. Wohlers (1998) gives an example where a Keltool insert was run in production conditions for more than one million cycles. One limitation for the process is the maximum size of 150×150×150mm but this has been overcome by some tool makers press fitting Keltool parts together to form a larger tool.

Another approach to the production of more robust tooling is to use the RP part as an Investment Casting form. A ceramic shell is formed around the part which is subsequently burnt out in a furnace to leave only the fired shell. Multiple parts can be shelled up simultaneously by hanging each part off a wax tree. Processes ideally suited to this are those which build RP parts in waxes such as FDM, Sanders and recently the Actua and Thermojet systems from 3D.

A slight modification to this process is PHAST and Dynamic Tooling's powder metal forging process. With PHAST, a ceramic shell is formed around an RP pattern. The pattern is removed and the shell is then filled with metal powder. The filled shell is then fired during which copper is infiltrated into the metal powder. The key advantage here is that shelling and filling take place in one operation (Wohlers, 1998).

Dynamic Tooling takes a slightly different approach. A ceramic mould is formed around the pattern which is then removed. Metal powder is then placed in the ceramic mould, which is then held at forging temperature and pressurised using a hydraulic ram. The result is 100% dense parts similar to the results found in Hot Isostatic Pressing (HIP) (Wohlers, 1998).

The last processes of note, in this section, are those technologies based around Electroplating and Electroforming. Keltool have demonstrated infiltrated tungsten electrodes for Electro-Discharge Machining (EDM) and Arthur *et al* (1995) produced electrodes by electroplating SLA parts directly with copper.

Two companies are now offering their own solutions. CEMCOM Corporation (1998) have developed the NCC Tooling System (nickel ceramic composite). The process uses an RP model of the core and cavity onto which nickel is electro-formed. This is backed by their patented Chemically Bonded Ceramic (CBC) which provides the support for the nickel shell when the RP pattern is etched away.

On a similar vein, ExpressTool (Warwick, RI) electroform a 1-2mm nickel shell onto an RP pattern or graphite mandrill (Wohlers, 1998). The shell is backed with epoxy resin and the pattern removed. The process produces durable injection-mould tooling but both processes are limited by the electroforming process which struggles to 'throw' nickel into deep holes.

2.4.3 Direct Soft Tooling

With Direct Tooling (hard or soft), developers are looking for ways to use sliced CAD data to generate the tool in one operation (no secondary processes are employed). The main advantage of this is the elimination of reverse geometries which influence the tolerances on the finished tool.

In the area of Direct Soft Tooling there has been extensive effort to advance the concept of Prototype Tooling. A natural candidate for this is DTM's Selective Laser Sintering. Current interest in this area, however, is focussed on 3D Systems Direct AIM™ Tooling. AIM™ stands for ACES Injection Moulding where ACES describes a proprietary process for the production of 'Accurate Clear Epoxy Solid' SLA parts.

Hopkinson & Dickens (1998) have shown that a solid SLA core and cavity can be generated, cleaned and mounted in a bolster. This tool can then be used for injection-moulding of most of the less aggressive polymers. Key to its success and longevity is the fill time and point of ejection. ACES resin is a poor thermal conductor and heat can build up in the tool rapidly if it is not monitored. This means that injection temperatures can be lower as the tool is not drawing off the heat as in conventional metal tooling. They have shown that a few hundred parts are within its capability which could be enough to satisfy fit and function requirements and will also allow for short runs in engineering plastics.

Another technology in this category is EOSINT Direct Metal Laser Sintering (DMLS). EOS are based in Germany and have developed their own version of the SLS process. EOS introduced their own solution to Rapid Tooling in 1994 through a modification on the existing EOSINT equipment to form DMLS. The subtle difference between DMLS and RapidTool is what places it in the Direct Soft Tooling category. Their approach was to attempt to go for complete laser fusion of metal powders placed in the machine. This was achieved through the development of a low melting point bronze-nickel powder which could be fully sintered with no secondary operations. Though not steel (they now offer steel powders for sintering), it gives enough detail and retains enough strength for short production runs in injection moulding.

The final technology of note is the adaptations made to the Spray Metal Tooling concept. A few research groups have been working on the idea of either spraying metals in layers through a predefined mask (Recursive Mask Deposition, MD*), or by using multiple axis spray metal heads to build up 3D objects with milling to flatten each layer before the next is deposited (Shape Deposition).

The MD* process deposits a layer of sprayed metal through a mask placed against the build volume. When the mask is removed, it takes any overspray from the gun and only leaves metal on the part. This is then shot peened to relieve stresses which build up in the Thermal Spray process and milled to maintain layer tolerances. Amon (1993) observes that there are issues of distortion which must be overcome if this technology is to compete. The technology still needs refining and Tromans & Wimpenny (1995) see benefits in finer deposition processes such as High Velocity Oxy-Fuel Spraying (HVOF).

2.4.4 Direct Hard Tooling

Direct Hard Tooling is the final category and many of the processes discussed are yet to reach commercialisation. This category is littered with research groups around the globe, all pushing the boundaries of what is possible. Direct Hard Tooling is focussed on the production of full scale production tooling capable of matching, or exceeding, the expectations of conventional machined tooling.

There are two approaches in this area. The first enhances current 'subtractive' processes by applying new technology to existing CNC milling machines. The second is to develop 'additive' processes which enhance the RT processes already discussed. To develop this field fully may well require a combination of additive processes to generate a direct tool and subtractive processes to finish it.

Milling and CNC milling are the long established methods for the production of tooling and they epitomise the classic 'subtractive' process. The RT processes which have been covered so far came about through the need to offer faster processes over conventional milling, in line with TCT and Concurrent Engineering (McOlash & Skibinski 1991) (Vouzelaud & Bagchi 1992). The growing interest in RT has forced CNC machine manufacturers to re-appraise their machinery to maintain their market share in the tooling field.

The results of this endeavour have been to radically increase the cutting speeds. The key to this is to increase spindle speeds from around 3000/10,000 rpm to, in excess of, 30,000/50,000 rpm. To increase spindle speeds by this amount required a complete re-engineering of the machine and the cutting tools used. Conventional spindle bearings will shatter at these elevated speeds and the solution was to develop virtually frictionless air bearings.

Wohlers (1998) states that it was the Japanese machine manufacturers who really pushed the process forward with the discovery that at these elevated spindle speeds the cutting head behaves like an ablative tool, instead of a cutting tool. They developed solid carbide cutting heads with polygonal cross sections which produce no heat so require no cooling, can be as thin as 0.4 mm and can cut thin walled sections down to 0.1mm in solid tool steel.

Throughput on these machines is the key to making them pay. The major concern is the deflection of the tool head as it changes direction. The machine is moving so fast that the cutting tip will flare outwards where deep cuts are required. Another problem which has hindered CNC milling from the beginning is getting the cutting head deep into the tool due to the size of the spindle itself. A solution is to add a further degree of freedom to the machine without loosing stability (Lhuillier, Lescalier & Barlier, 1995).

Current 'state of the art' systems awaiting launch are the Variax and Hexapod systems. They have addressed the problem of adding a degree of freedom without loosing stability by mounting the cutting head on a platform suspended above the bed by six linear actuators. These can tilt the head in almost any direction and allows the tool to get inside a cavity to machine difficult geometries, such a deep draft angles.

From an 'additive' standpoint the direct fusion of metal powders using high powered (>1000 watts) lasers is considered the Holy Grail of RT. Wohlers (1998) notes two processes are reaching commercial viability, Laser Engineered Net Shaping (LENS) from Sandia National Laboratories and Direct Light Fabrication from Los Alamos National Laboratories. Both are similar in that they pass metal powders directly into the focal point of a high powered laser. The laser is focussed onto the part to be built and forms a localised melt pool through which metal powder is added. The process is layer by layer and has demonstrated fully densified metal components in a variety of complex geometries. The test parts demonstrated, so far, tend to be thin walled which will naturally dissipate excess energy to the surrounding air. What has yet to be seen is how these two processes cope when building tools with sections of, say, 100mm thick (excess heat may set up stresses in the tool as it cools).

Building a solid metal tool presents other problems, the deposition process rarely results in an even layer of material as defined by the CAD slice. Two more processes are under development that hope to address this and can be viewed as both 'additive' and 'subtractive'. Fraunhofer's Controlled Metal Buildup or Laser Generating process lays down material in the same way as LENS but then uses a high speed cutter to mill off the excess material and produce a level surface for the next layer Klocke *et al* (1995). The milling head has multiple axes to allow the sides of the part to be shaped as well.

A second approach was developed as part of a Brite EuRam funded project to develop fully dense metal tools. Two avenues were explored the first being to mount a MIG (metal inert gas) welding torch on a multi-axis robot gantry and build up solid metal parts through the controlled deposition of a weld bead (Spencer & Dickens 1995). This met with limited success and milling was required to level off each layer before the next could be started.

The same project produced an alternative method whereby tool steel powder was laid down, as in SLS, and then scanned with a high powered laser to selectively fuse the tool. This was the first process of its type to produce a full demonstration tool and achieved almost complete densification with little distortion of the part. This process is now being extended to include parts with functionally graded mixed matrix structures (concentrated zones of different material inside the same volume) with research just under way at the Rapid Manufacturing Group at De Montfort University, UK.

The final technique, under development, is Laminate Tooling and is covered in greater depth in Chapter 3.

2.4.5 The State of the Industry

The size of the Rapid Tooling market is hard to define as so many processes are still under development. Wohlers (1998) has identified the secondary (indirect) RP market as based around the production of tooling through the use of existing RP technology. This sector grew by 11.9% in 1997 to a value of $320.6 million.

The potential size of the Rapid Tooling market, if all these systems become commercialised, can be gauged by assessing the existing tooling market using conventional approaches. Wohler (1998) estimates that the world-wide production of injection and compression moulding tools currently ranges from less than $4 billion to more than $10 billion. Estimated figures for the US are $2.2 billion and for Japan $1.7 billion which represents 18% and 44%, respectively, of the world tooling market.

Chapter 3: Laminate Tooling

3.1 Introduction

Laminate Tooling is one of the Rapid Tooling processes identified in Chapter 2.4. Within the categories identified in that chapter, Laminate Tooling is defined as a Direct Hard Tooling process.

Laminate Tooling is similar to the Laminated Object Manufacturing (LOM) process described in Chapter Two. Though Laminate Tooling appeared a decade before the LOM process, Laminate Tooling is best defined by Feygin (1988) (the inventor of LOM), in his patent (EPO 272 305 B1) as *"the production of an integral three-dimensional object formed from individually contoured laminations of the same or gradually varying shape"*. LOM is associated with the systematic bonding and laser cutting of sheet paper to form complex 3-dimensional prototypes. However, this concept can be extended to any sheet material, be it organic (paper, foodstuffs, biomaterial) or inorganic (ceramics, polymers, metals).

Laminate Tooling is a 'direct' approach to the generation of production tooling, in that sliced CAD data from a 3D model is exported as 2D slices. It is these 2D slices or, more specifically, their boundaries, which define the cutting path for some form of cutting device (be it laser, abrasive waterjet, plasma, EDM wire erosion etc). Individual laminates are cut from a sheet material and, on assembly, these laminates form the pre-defined tool.

For the purpose of this thesis the use of sheet metal as the laminating medium will be considered. There is, currently, interest in the possibility of constructing both prototypes and tooling from layers of ceramic sheet material driven mainly by the problems which have been encountered in the attempts to directly sinter ceramic powders using the SLS process (Lee, 1996). Ceramics hold many possibilities for high performance tooling in the near future. Newman *et al* (1995) have been working on a process called Computer Assisted Manufacturing-Laminate Engineering Materials (CAM-LEM) in which sheets of ceramic are laser cut and assembled, followed by firing, to produce small detailed ceramic parts. At present, the process has its limitations and has not been extended to production tooling and for this reason it will not be considered further.

3.2 Laminate Tooling Development & Research

The idea of building a complete part from individually cut laminates of metal is not new. The technique has been consistently used in the production of transformers, electric motor stators and rotor elements for almost a century. Due to the nature of the magnetic fields and induction currents generated within these parts, there are benefits in constructing the assemblies from thin laminates of steel. In these products, one laminate is identical to the next and punching or blanking the desired profile from a sheet material produces each laminate. The laminates are assembled and bonded ready for further operations towards the finished item. Though simple, this technique is a far cry from the laminate tooling now being developed. The fundamental distinction is that almost every individual laminate in a Laminate Tool has a different profile from that of its neighbour.

In discussing how development of the various laminate tooling methods began it is also important to consider why they began. Essentially, all the techniques which will be discussed are substitutes for what has been conventionally produced from cutting or machining solid material. The specific advantages of this will be discussed in detail later in this chapter but it is worth addressing the question as to why construction of solid parts from laminates should be advantageous at all.

Generally, the advantages are specific to the processes which have been developed over the years. In the example of transformers, there are benefits to be gained using laminates in maintaining a magnetic field, which is difficult if construction were from solid steel. In the processes which will be discussed in this section, the benefits of a laminate construction are gained through some shortfall of machining a part from solid material.

3.2.1 Laminate 3D Metal Forms

The first example of laminate construction from individually profiled steel sheets is described in Matteo & Paul's (1976), U.S. Patent 3-932-923, in which they describe a replicating device for the production of 3D parts with complex geometries. By setting up a shaped mandril of the part which is to be replicated on a lathe, and using a position transducer and stylus, a contour can be traced on the mandril (one incremental vertical plane at a time) as the mandril is slowly rotated. This information can then be used to cut a sheet of steel of a pre-defined thickness which represents the motion of the stylus of the mandrel on that planar section. The sheet could be cut with either milling machine or laser to produce each laminate as the transducer moves across the mandril at set increments. The individual laminates could then be assembled and bolted in order to form a replica of the mandril. Using laminates enabled complex 3D objects to be broken down into discrete 2D slices which could be readily duplicated and assembled to form a 3D solid. This technique was incapable of producing tooling due to the difficulty in getting the stylus to trace the internal features of a rotating mandril to form, say, a tool cavity. It was, however, the first attempt at constructing 3D objects from 2D elements and paved the way for subsequent laminate tooling research.

Matteo & Paul's concept had one major flaw. The stylus was directly attached to a position transducer to generate the cutting profiles needed for the laser cutting operation. Producing the mandril and then mounting it on a rotating platform was fraught with problems but was the first real attempt to construct 3D forms from 2D slices of data.

3.2.2 Laminate Blanking Tools

The following year, Professor Takeo Nakagawa of Tokyo University (1977, 1980 & 1981) made the intellectual leap through the incorporation of new technology and is now accredited as the founder of Laminate Tooling. In 1977 he addressed the problem of producing rapid, low cost, blanking and deep drawing tooling for Japanese industry. Again, necessity was the driving force that led him to look for alternatives to conventionally machined solid blanking dies.

Shingo (1985) states that at this time, the Japanese were pioneering tooling systems which now form the standards around the world. The Japanese realised that industry required tools faster and with regular modifications to keep them competitive. Nakagawa (1995) realised that to do this was difficult in industries using punches and deep drawing equipment, where much of the cost of the product could be accounted for by the production costs of the dies and presses themselves.

Schlichting (1996) notes that the government forced the Japanese 'domestic' tooling market to grow from $2 billion in 1975 to $7 billion by 1991. Such was the pressure on tooling manufacturers to innovate and speed up tooling production that, in 1977, a law was passed that half of all the tools produced in Japan should be produced by CNC. This was at a time when the concept of RT had not been considered in the West.

Nakagawa realised that the working part of a blanking or deep drawing tool was the top surface of the die. The remainder of the tool was mainly for support of this surface. He began a ten-year project to develop cheap and rapid tooling for these applications. The approach he took was to build the tool with horizontally stacked laminates of steel, which were cut by laser or EDM wire cutting. The laminates were stacked horizontally to withstand the huge compressive loads that the tool would be subjected to as shown in Figure 3.1.

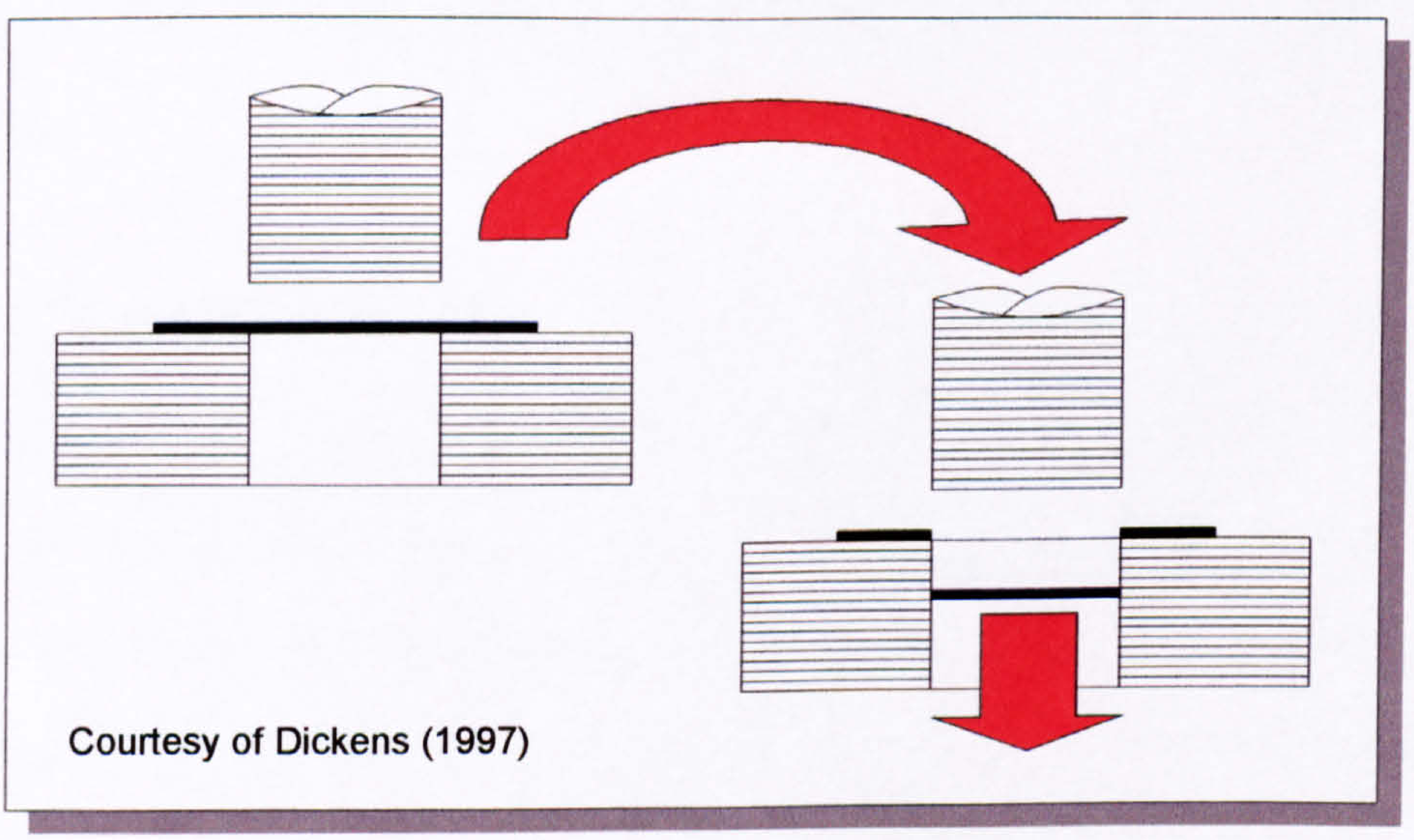


Figure 3.1 Horizontally stacked laminate blanking tool

Nakagawa *et al* (1984) chose a laminate thickness of 3.2mm mild steel, mainly due to its availability. Each laminate was cut with a laser, except the top 'cutting' plate which was cut using wire EDM from a tough 'bainitic' steel. Nakagawa (1995) also notes that such was the success of this work that the process was taken up by Hanai Engineering in Japan who, up to the publication of that data, had produced 10,000 deep drawing and blanking tools constructed from laminates.

Laminate tooling only came about as technology improved and material costs declined. By the early 1980's Nakagawa showed that it was possible to produce laminate tools cheaply, but only after the laser became commercially available. To cut steel sheet by any other process was either too inaccurate (plasma cutting) or too slow (wire EDM). The laser was the first cutting mechanism that cut sheet metal with minimum affect from heat distortion at the cutting zone and with a fine enough kerf width (0.1mm) to allow the production of detailed profiles. Kirkpatrick (1994) observed that high definition plasma and abrasive waterjet cutting have sent the cost of high definition profiling equipment falling and this is now considered the first 'enabler' to the development of Laminate Tooling.

The second 'enabler' to laminate tooling was CAD. With Nakagawa's earliest work, each profile of the final tool had to be individually drafted and then entered into the NC terminal sheet by sheet. The development of CAD and linking CAD directly to NC machinery revolutionised this process. Huge quantities of layered data, generated from the sliced CAD model, can now be downloaded, nested and a tool path defined in minutes.

Following Nakagawa's work, the uptake of laminate tooling around the world was slow. At this time, industry did not take seriously the concept of assembling individually cut steel laminates to produce a tool. However, with the advent of RP and later Rapid Tooling, researchers began to see an opportunity for Laminate Tooling which did not exist before. With both Matteo and Nakagawa the use of laminates was driven for the need to an alternative to the conventional approach.

By the early 1990's, a variety of different research groups began exploring how this simple process of cutting and assembling pre-cut sheets could be applied to various different tooling applications. It was at this time that the various 'indirect hard & soft tooling' approaches discussed in Chapter 2 began to appear. In those processes, which used relatively lower pressures to form part from, the indirect approach proved very suitable. However, where Rapid Tooling was required for large-scale (500x500x500mm) high-pressure applications there were limitations where these approaches were concerned. These limitations include:

- Loss of accuracy, in the case of Thermal Spraying, where the tool was formed over a master. The excessive build up of metal can lead to thermal distortion, (Segal & Cobb, 1995).
- Inadequate build volume in the case of infused SLS and 3D Printing, Sachs *et al* (1995), and the CAM-LEM process.

In the search for rapid, scaleable and robust tooling, one obvious solution was to adapt the work begun by Nakagawa. CAD modelling and the concept of generating sliced data were well established by this time and so a variety of research fields in this area began to appear.

Within the boundaries of laminate blanking tools, the first group to attempt to build on Nakagawa's work was the Danish Technological Institute. Schreiber and Clyens (1993) approached Laminate Tooling from the view of applying the work which Nakagawa did for Japanese industry to Europe. They realised that for Laminate Tooling to work in Europe, some of the fundamental points that Nakagawa discovered in the early 1980's had to be re-addressed.

Their work began by building a laser cut laminate blanking tool, but mainly focused on the problem of availability and the quality of sheet steel in Europe. At this time, they found too many discrepancies in the thickness and quality of the sheet. Though they only produced the cutting plate for this demonstration, they did highlight the problem of the annealing effect on the hardened steel sheet during the laser cutting process and the effects of elastic deformation when the sheets of laser cut laminates were assembled. For blanking, they identified and discussed the properties of three, bainitic, hardened, alloy sheet steels these were Hardflex, UHB Arne and UHB 20C.

3.2.3 Laminate Forming Tools

As an extension to the work on blanking tools, other groups began to look at the production of forming tools. Four groups are actively exploring the potential of this field.

After Nakagawa's early exploits, the next group to investigate the potential of Laminate Tooling was Walczyck and Hardt (1994) at the Massachusetts Institute of Technology. They had been considering an adaptive, closed loop system for the rapid production of sheet metal forming dies. They wanted to produce a machine which could rapidly produce a die over which sheet metal could be formed.

At first, they considered a pin array, whereby metal pins were set up side by side in a large array. The pins, when loose, could be formed into a desired shape using an actuator and then fixed in place by a bracing jacket around them. This had its limitations. In seeking an alternative solution, they realised that they could use a CAD model to define the die surface they wished to form and then recreate it with laminates of laser cut sheet steel.

The key difference with their approach, over that of Nakagawa's, was that once the laminates were cut, they were assembled vertically and then bolted together. The problem with bolting horizontally stacked tools is demonstrated in Figure 3.2.

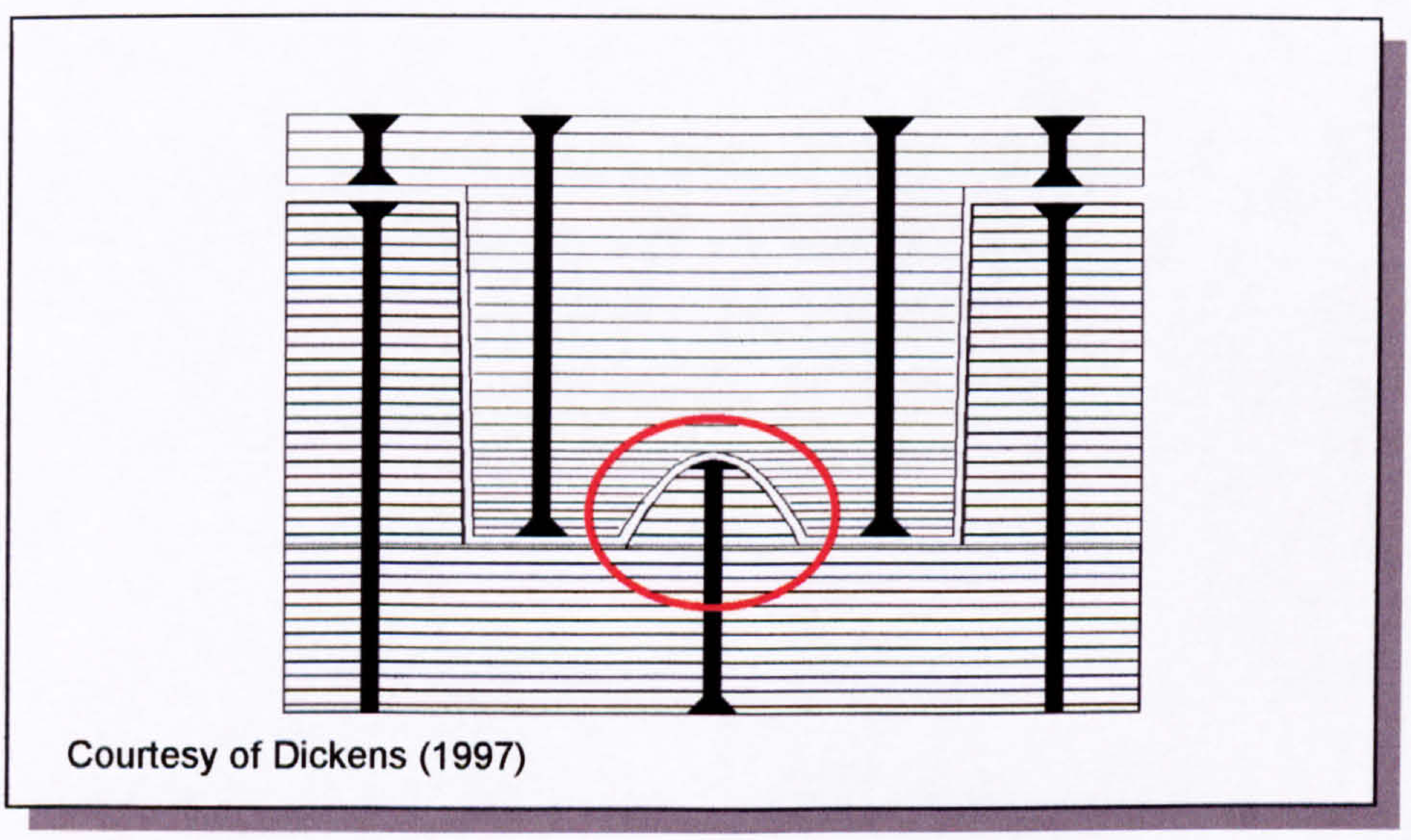


Figure 3.2 Problem of clamping horizontal laminates

Horizontally stacked laminate forming tools result in complex clamping arrangements to take into account islands or internal features. Clamping the laminates vertically overcomes some of these problems and is demonstrated in Figure 3.3.

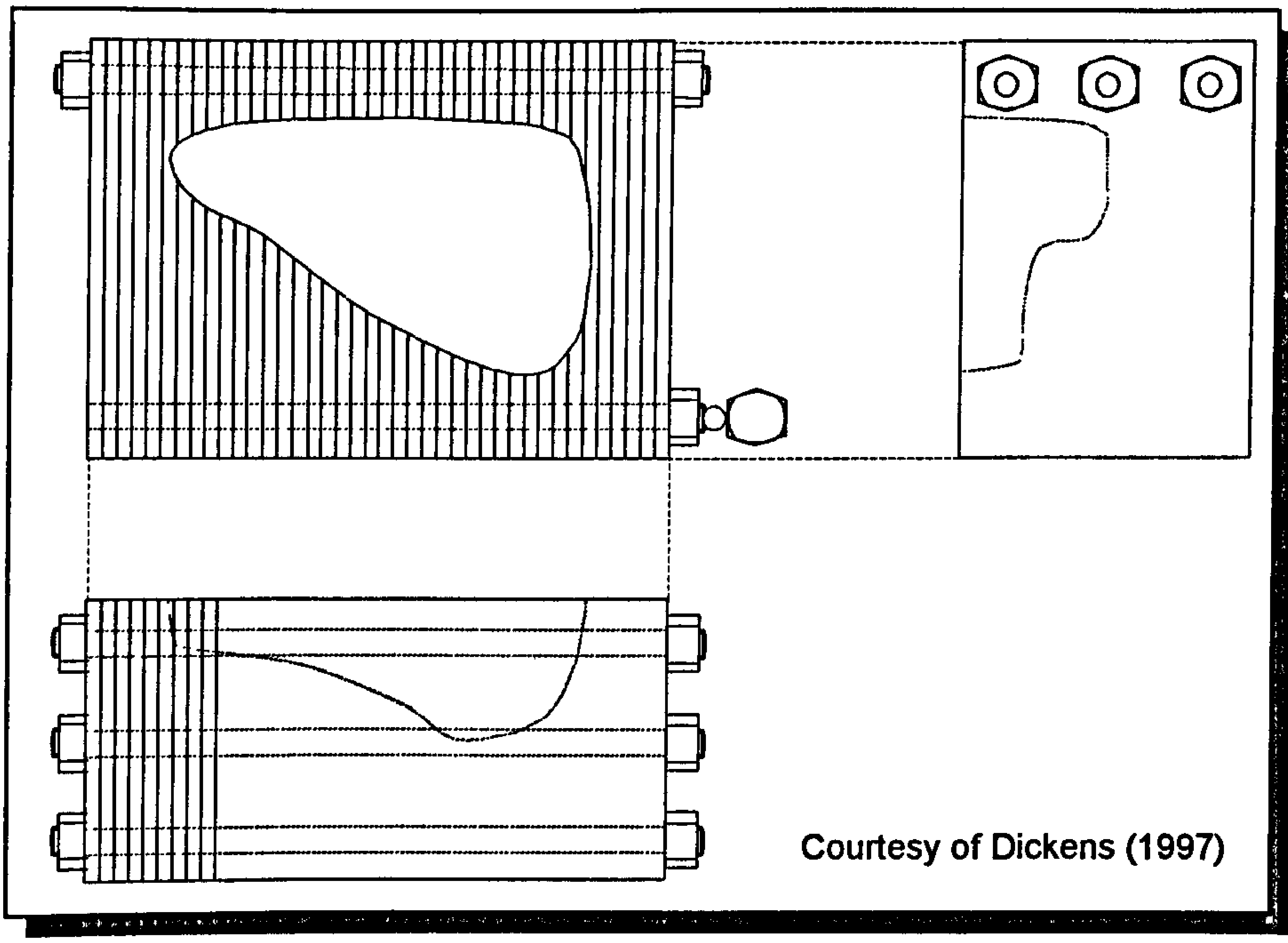


Figure 3.3 Clamping vertically stacked laminates

Vertical clamping results in far greater rigidity to the stack, particularly the female half of a tool. Even so, this may result in problems where tall protrusions occur that may require additional clamping, particularly in the male half of the tool as shown in Figure 3.4.

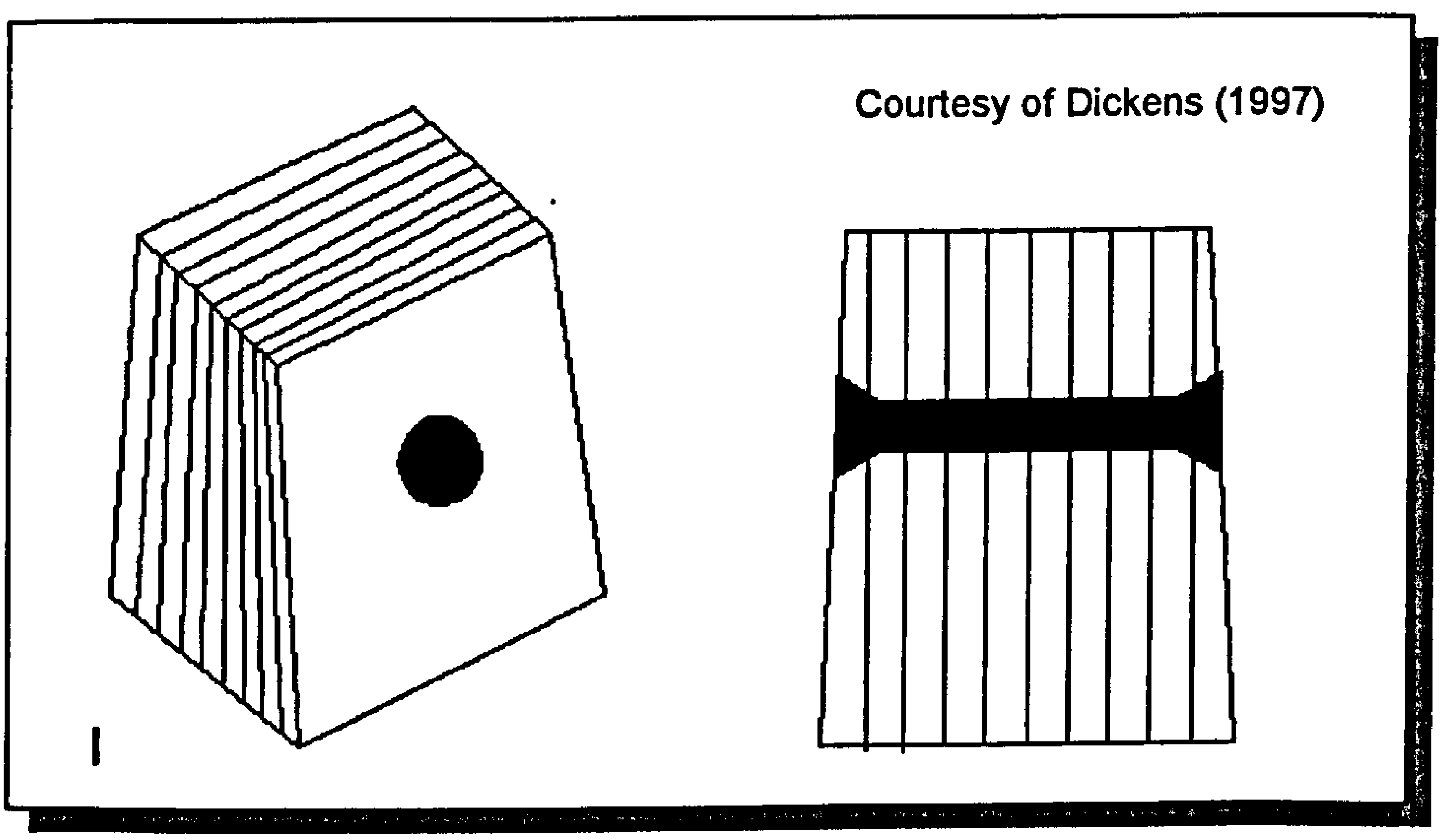


Figure 3.4 Additional clamping of tall protrusions

One further advance that Walczyck & Hardt wished to make was the use of a profiling laser with an extra degree of freedom. The intention here was to overcome the problem of stepping which inhibits almost all Rapid Prototyping &Tooling (RP&T) processes.

Stepping is particularly acute in a laminate tool where the laser cuts perpendicular to the sheet; the assembled laminates have a stepped appearance dependant on the thickness of the sheet steel used. A thick steel sheet will require fewer profiles to produce a tool but will result in larger steps, whereas, if thinner sheet were used, particularly where small radii must be reproduced, then the definition is increased. Figure 3.5 demonstrates this.

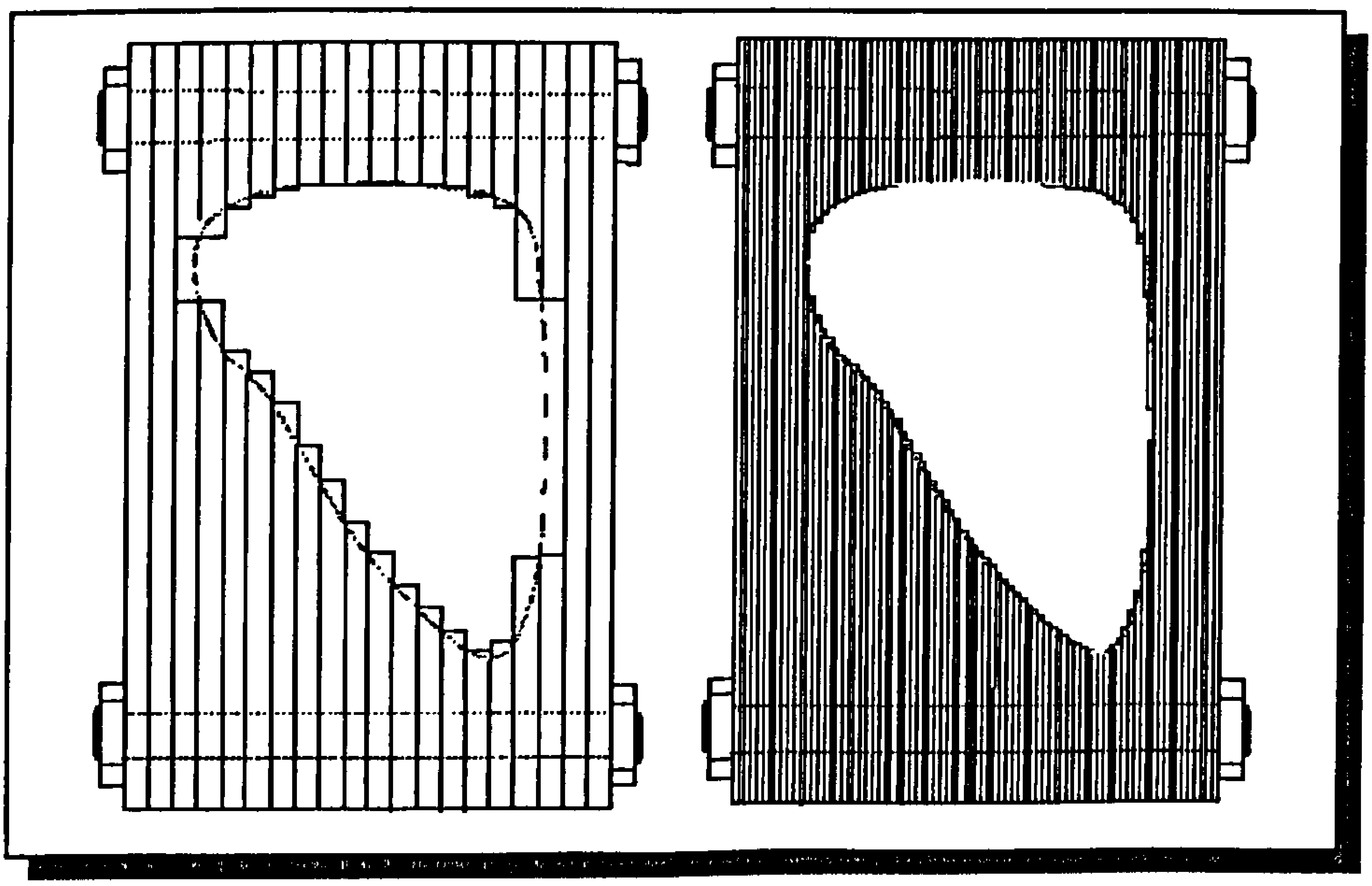


Figure 3.5 Trade-off of thick and thin sheets in tool construction

In addition, thick sheets give good rigidity to the tool but require extensive finishing operations and thin sheets require little finishing but the rigidity of the stack is lost. The benefits of an extra degree of freedom are shown in Figure 3.6.

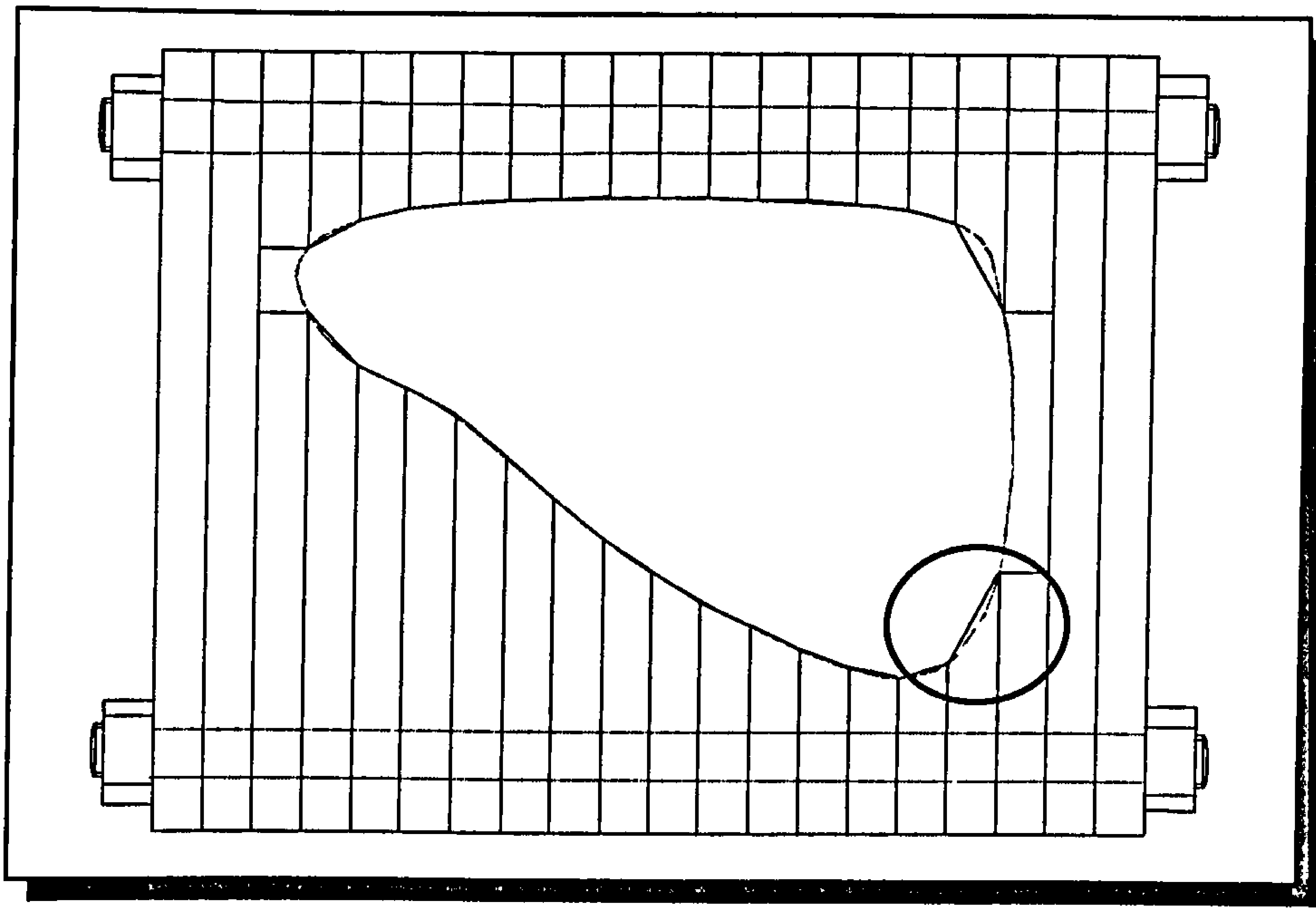


Figure 3.6 Thick sheets cut with a 5-axis profiler

There are limitations to the maximum bevel which can be achieved with a 5-axis profiling laser. Any angle of cut greater than approximately 45^0 will result in either deflection of the beam as it penetrates the steel, or in excessive heat which results in large burrs. Even so, their research resulted in the development of a continuous system which was called "Profiled Edge Lamination" and the proposed machine to produce laminated dies was called "Die Lamination Profiling".

During the same time, the Bremen Institute for Applied Beam Technology were developing the Laser Assisted Sliced Prototyping. Engler *et al* (1997) began by looking at the construction of three dimensional shapes constructed from sheet steel which were simultaneously laser cut, assembled and laser welded in one automated system. To reduce the stepping which occurs in most RP processes, they also explored the use of a profiling laser to reduce the stepping and achieve near net shape. The test tool they produced, as with Nakagawa's tools, had horizontally stacked laminates. This may appear as a step backwards but the group was concerned with issues relating to the 'shut-off' faces in laminate tool construction.

With a vertically stacked laminate forming tool, the two halves of the tool must meet at the parting line to form sheet steel in. If the parting line is flat and perpendicular to the stacked laminates then the ends of the laminates will abutt on closure of the tool with no adverse affects. Forming tools are rarely that simple and where vertically stacked laminates are used then the shut off faces will be angled. This can lead to premature failure of the laminates at the end of the shut off face as demonstrated in Figure 3.7.

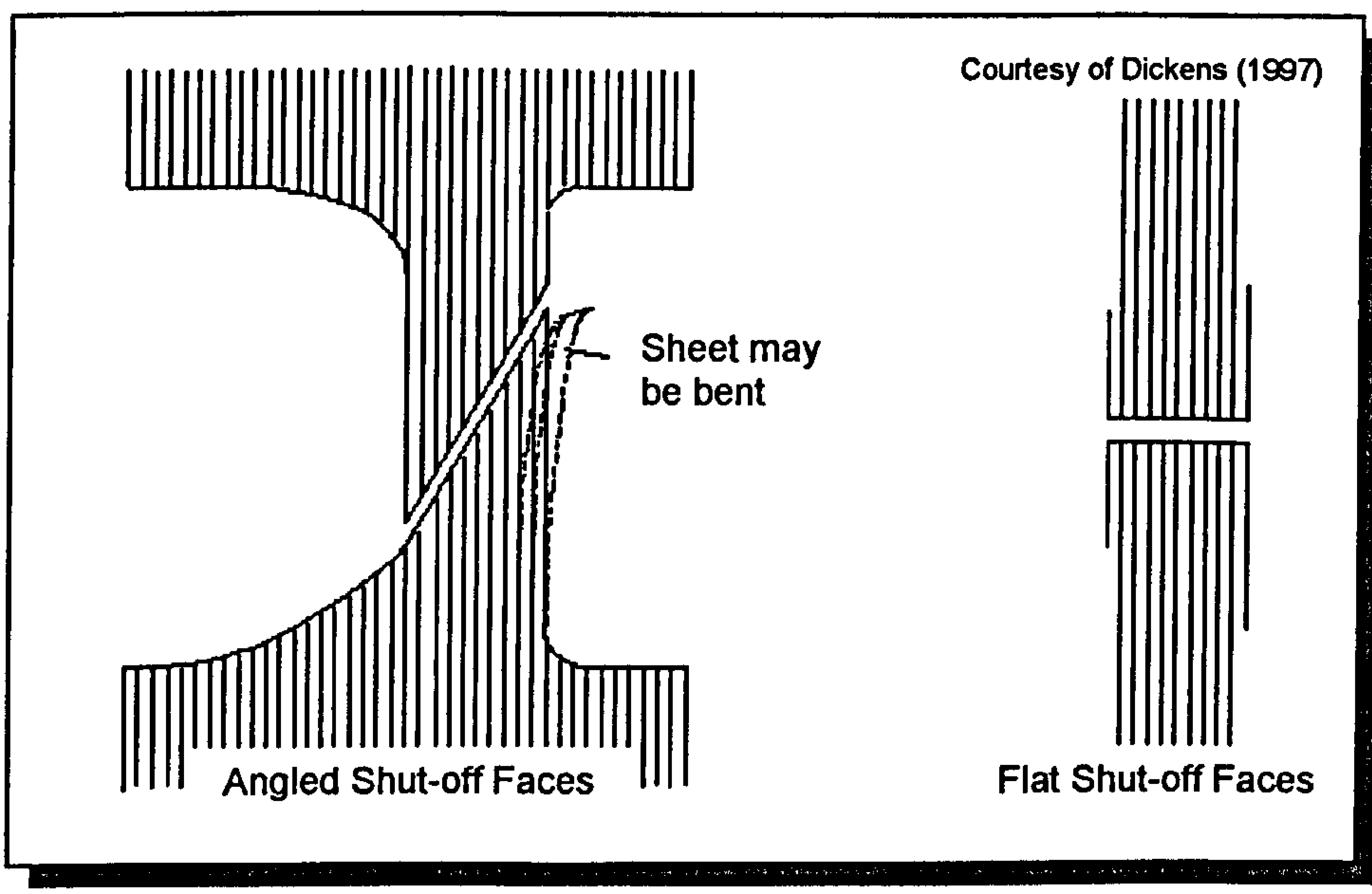


Figure 3.7 Problem with shut-off faces on vertically stacking

For the Bremen project each profile for the tool was cut from 1mm thick sheet steel, 400×400mm in area. During the project, they became particularly interested in the fact that as each profile was cut to form the male forming tool, the off-cuts could be assembled to form the female of that tool. The greatest problem highlighted by this work was the welding of each sheet to the sheet below, during assembly.

Welding was used to overcome yet another issue specific to Laminate Tooling, that of containing the assembled laminates so that they behave as a solid mass. Simply using bolts to clamp the laminates together is insufficient. The analogy is that of a pack of cards and is demonstrated in Figure 3.8 and 3.9.

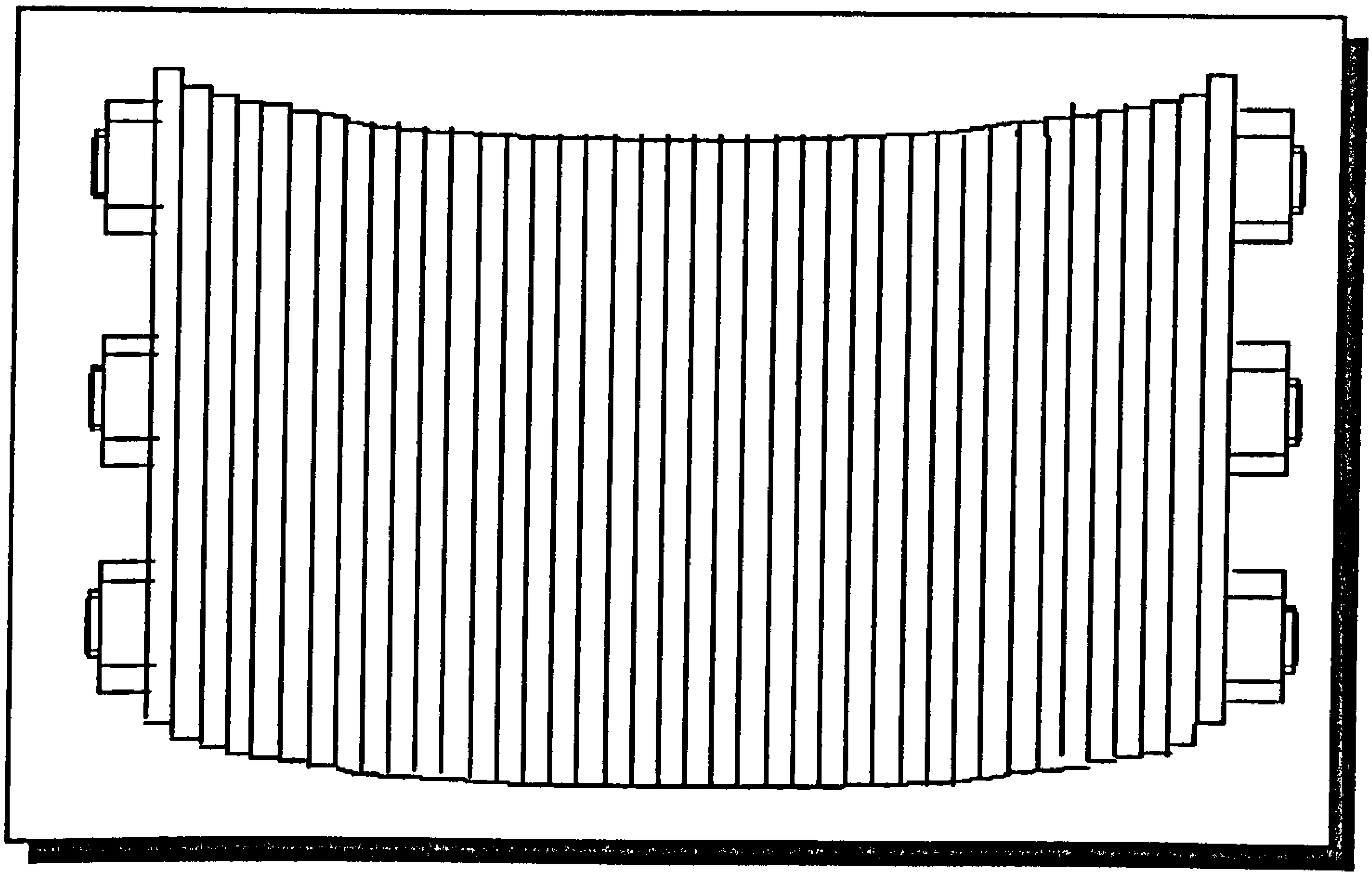


Figure 3.8 Vertical distortion through sag on the through bolts.

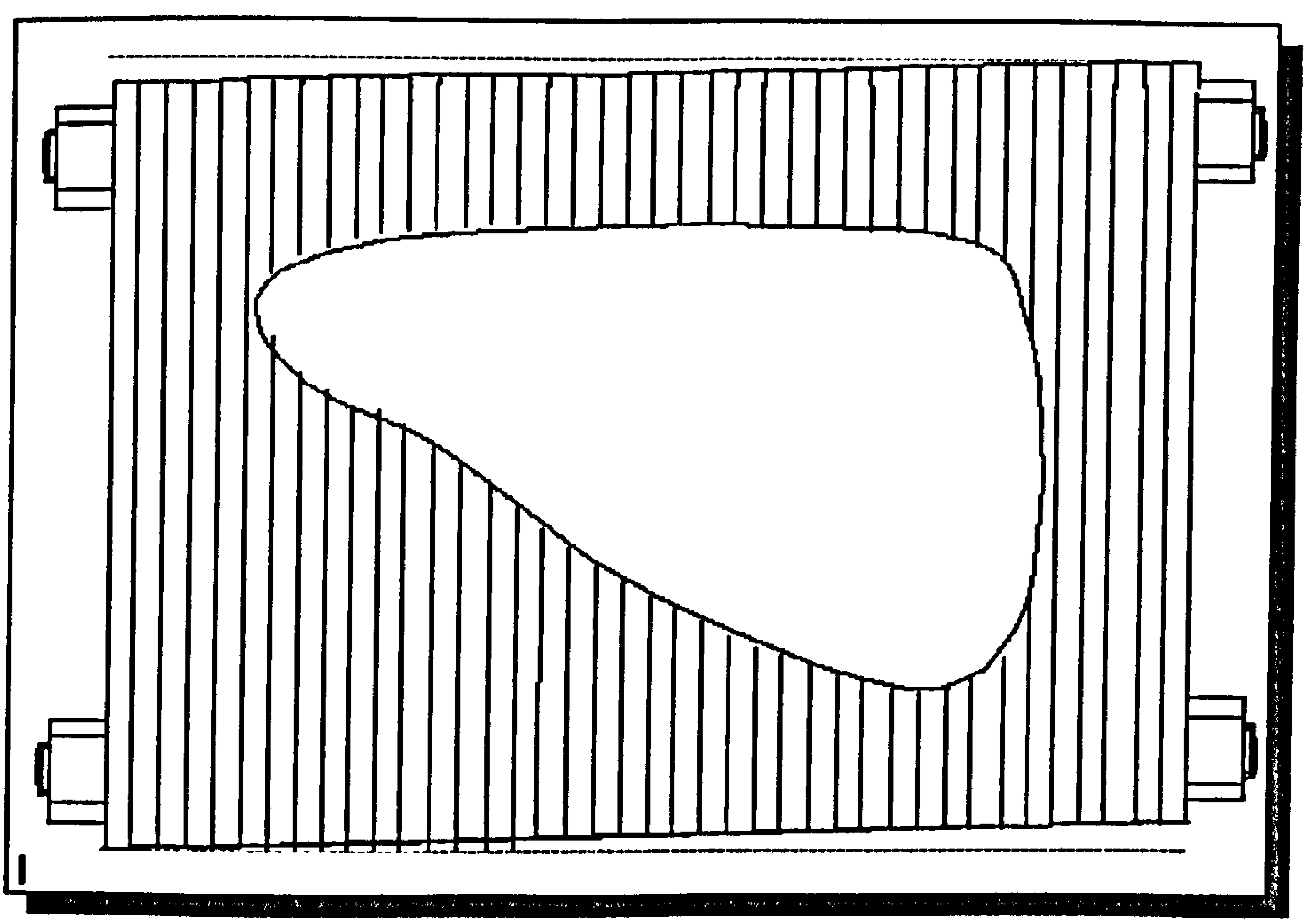


Figure 3.9 Horizontal distortion through incorrect alignment

Sheet steel is rarely flat and a laminate stack tends to behave like a tightly coiled spring. If the bolts are unevenly tightened then this too will deform the stack. The Bremen research Engler *et al* (1997) incorporated 'spot welding' in key locations on each sheet but this also resulted in distortion and buckling of the laminates. Even so, they concluded that the work was a valid 'direct' method for the production of forming tools compared to existing methods.

On a similar theme, a collaborative project, consisting of Warwick, Leeds & Liverpool Universities and industrial organisations, has developed a comprehensive program for furthering Laminate Tooling into a variety of different fields. Adams and Wimpenny (1998[1]) explain that the "Large Scale Tooling for Rapid Manufacturing" (LASTFORM) project, intends to apply Laminate Tooling to a variety of applications including injection moulding, resin transfer moulding and, in particular, press form and super plastic forming tools.

The project is structured so that a variety of fundamental issues relating to the production of Laminate Tooling are addressed and, at present, this is centred around the bonding of laminates to ensure rigidity in the finished tool. The bonding of laminates has been divided into the three categories of; mechanical fastening, brazing and welding. For the experimental work, 2mm thick sheet was used between which a variety of bonding agents were applied and the success of each was assessed. This work is still to be completed.

As mentioned previously, the final group in this area is, again, that of Professor Nakagawa's at Tokyo University in conjunction with the Toyota Car Company. Himmer

(1998) explains that the project was an attempt to produce large-scale forms over which car body panels could be formed. The work was similar to the work done at the Bremen Institute, mentioned above, but differed in that each horizontal sheet was first stacked then laser cut and laser welded in one operation. The intention was to weld each laminate to the laminate below and this was repeated to form a very rigid structure. A secondary High Speed Milling operation was then employed to finish the tool.

As with the Bremen work there were still the problems with distortion of the laminate stack due to the heat which builds up through both laser cutting and welding. In addition, the welding caused brittleness at the edges of each laminate which led to de-lamination and there were problems with supporting the stack, as overhang features were produced. Even so, Toyota tested a working tool and this was the first laminate tool to incorporate two thicknesses of sheet steel to enhance the detail of the surface of the tool and reduce the finishing required.

3.2.4 Laminate Tooling for Polymer Processing

During 1994, the Centre for Rapid Prototyping at the University of Nottingham became involved in the first practical project to produce a laminate tool for industry. Dickens *et al* (1996) notes that the Centre was approached by Simco Industries Inc. based in Roseville, MI, to see if it was possible to reduce the cost of tooling production. A few months prior, Ford Utica had approached Simco to produce a two part, eight cavity, mould for forming foamed urethane car door inserts. The tool was to be produced in aluminium, to minimize weight, and include integral cooling channels. Simco were keen to reduce the costs of manufacturing large-scale aluminium moulds which required a large amount of material removal using CNC milling. Conventional machining resulted in lead times per tool of 6-8 weeks with costs per tool of $26,000-$35,000 and this had to be drastically reduced.

Initial research showed that the fastest way to produce such a tool would be to construct the tool from individual sheets of aluminium. The laminates would be stacked vertically with a laminate thickness of 1mm. 1mm thick aluminium sheet was readily available and relatively inexpensive. In addition, the thickness of the laminates would give the required finish to the tool considering that the foam parts produced from the tool were not visible on the cars and therefore their surface finish was not critical. In total, the two halves of the tool had 1600 individual laser cut laminates created as individual DXF files which were fed to an NC laser. The tool is shown being assembled in Figure 3.10.

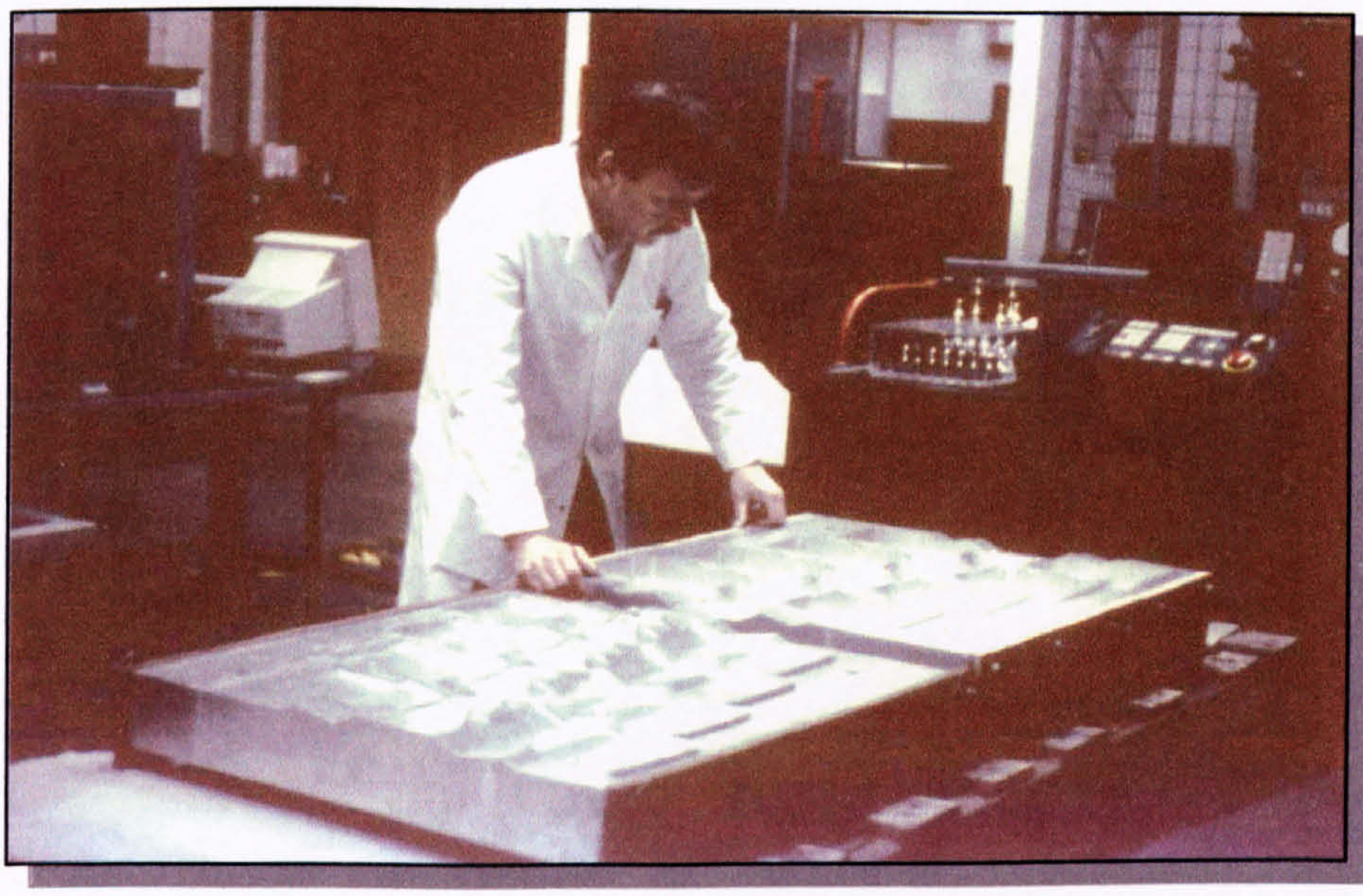


Figure 3.10 Laminate urethane foam-forming tool

It was the first laminate tooling project to compare the cost and time to produce a laminate tool against the conventional methods of casting or NC machining from solid stock. Considering this was a first attempt, the results matched and marginally undercut the production costs and lead times for the conventional method.

The project also incorporated 'conformal cooling channels'. In conventional tooling, the cooling channels are usually drilled in a straight line. However, the cavity may be highly complex and curved. In this situation, some parts of the cooling system may be much further away from the cavity than other parts. It is possible to have slightly more complicated cooling systems where cooling pipes are cast into aluminium tools. However, these are still limited by the minimum bend radius of the pipe-work and their inability to follow the contours of the cavity. An example of this difference is shown in Figures 3.11 and 3.12. The benefits of conformable cooling channels include:

- Variable cooling in different parts of the tool.
- Varying the mechanical properties of the moulded part.
- Control of the direction of solidification.
- The channels can be of any cross-section.
- Channel cross-section can be changed along its length.

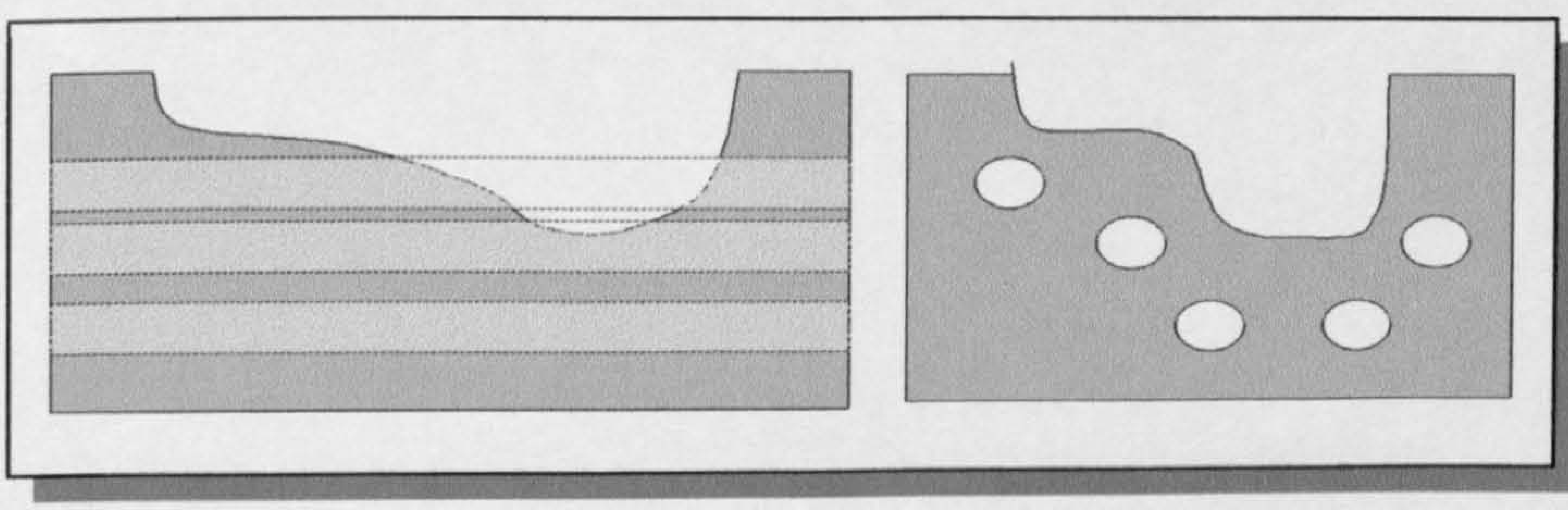


Figure 3.11 Conventional cooling channels in straight lines

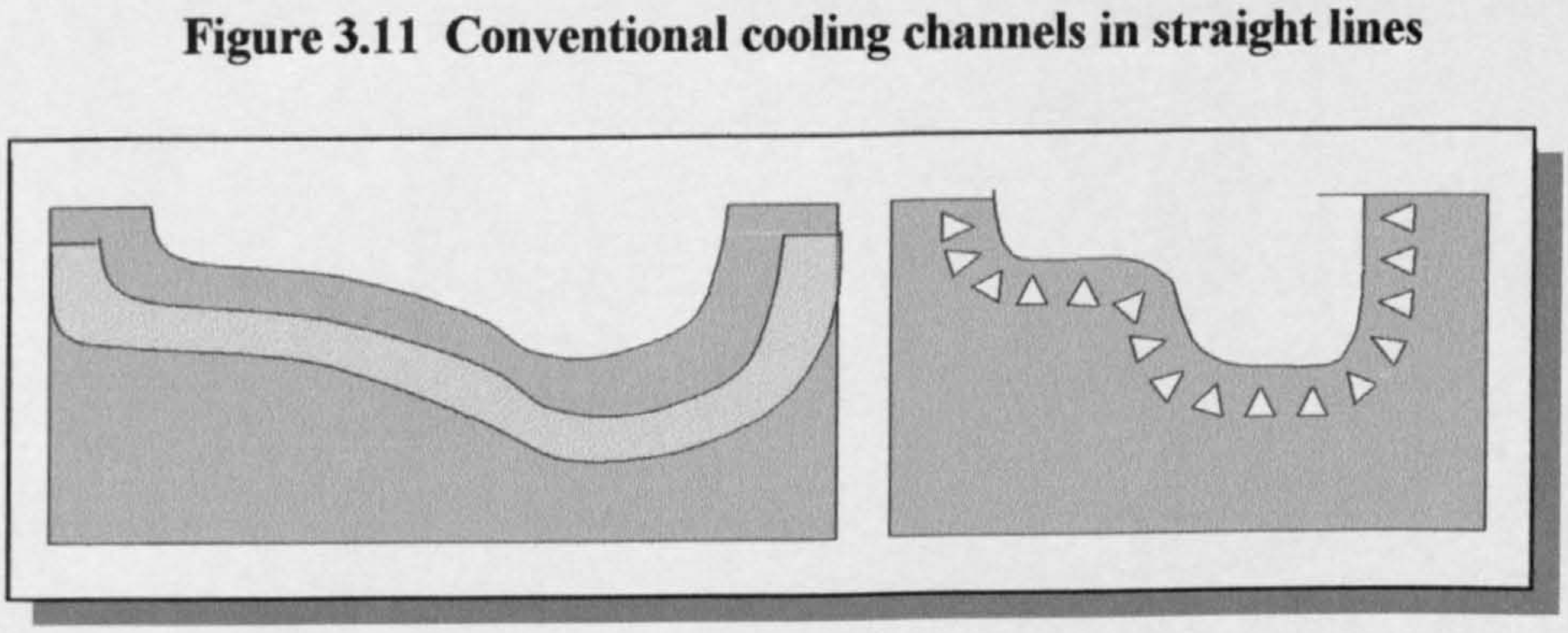


Figure 3.12 Conformal cooling channels in laminate tool

Problems highlighted by this work centred on the prevention of coolant leaking through the un-bonded laminates which was overcome by the inclusion of copper pipes. Upon completion, the tool was delivered to Ford and have had it in full production to this day.

During the work for the SIMCO project further research was undertaken to explore the possibility of exploiting the gaps between un-bonded laminate sheets to pull a vacuum. The concept was to produce large-scale laminate tools for Thermoforming and represents a simple thermoform product such as a mousse pot. The laminate tool is shown in Figure 3.13.

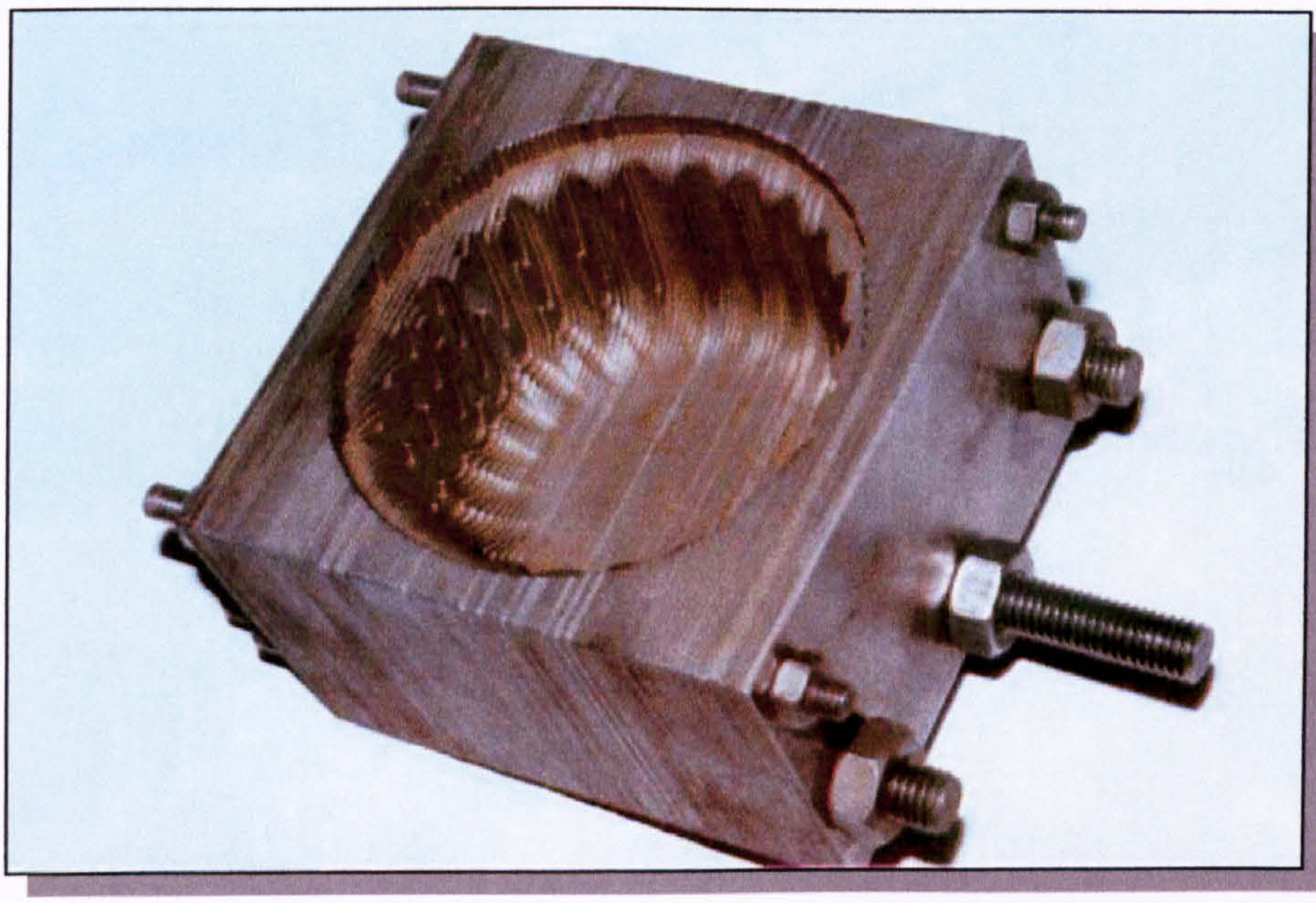


Figure 3.13 Laminate thermoform tool

This work was initially part of a degree thesis by Wilcox (1994) and was extended by Soar & Dickens (1996[1]) to encompass the feasibility of finishing such a tool with stereolithography EDM electrodes. The project was successful in that the tool produced perfectly adequate thermoform parts from it but the costs of producing the tool, compared to a conventional tool was prohibitive.

3.2.5 Laminate Tooling for Injection Moulding

The field of Laminate Tooling for injection moulding began in the early 1990's. It was quickly realised that, where large scale tooling was required for injection moulding, Laminate Tooling could offer a rapid solution. A die constructed from sheets of steel should be able to withstand the pressures and heat present in the moulding process. The first paper to be published after Nakagawa, relating to Laminate Tooling, was by Glozer & Brevick (1992), of Ohio State University, USA. They undertook an investigative study to see if Nakagawa's work could be modified to produce a prototype injection mould tool. They identified the benefit of using CAD data directly, to produce the tool. As in Nakagawa's work, they used horizontally stacked, 25mm thick laminates to form a mould for an oil sump. They identified the following benefits to the laminated approach:

- When cutting the sheet metal, it is possible to cut the cavity and core halves simultaneously.
- Laminates in the production tool could be replaced to allow for sliders and different undercuts.
- Intricate cooling channels could be designed into the tool as it is constructed from 2D slices.
- Different thickness laminates could be used in the same tool to define tight curves and flat faces.
- By interchanging laminates, experiments with gate design, surface finish or geometry could be done without reworking the tool.

Each of the laminates for the test tool was cut using EDM wire-erosion and the material was 2024-T3 aluminium. The mould was run on a 750kN injection moulding machine and produced over 400 parts. These parts were then tested for finish and accuracy.

The next significant study undertaken in the field of injection moulding was the production of a laminate test-die produced by the Centre for Rapid Prototyping at Nottingham University. This work formed part of an undergraduate thesis by Gross (1996) and was some of the original research undertaken by the author, Soar *et al* (1997). The production of this tool forms the next section of this chapter to demonstrate the typical construction of a laminate tool.

The key differences with this work, over that of Glozer and Brevick, was to use 0.5mm hardened steel sheet (CS70 grade, cold rolled) which was laser cut and stacked vertically prior to clamping. The key benefits in using vertically aligned laminates (the laminates are perpendicular to the parting line and not parallel) is the level of detail which can be achieved on the face of the tool. This also eliminates the possibility of 'islands of laminates' which can occur in laminates stacked horizontally. The concept was to assemble two tools; the first had all the laminates bonded using an Epoxy resin and the second had its laminates un-bonded. In the second tool, clamping plates were used to keep the laminates in place and prevent the laminate stack from warping. Sheets 0.5mm thick were chosen to see if the level of detail could be increased through the reduction in stepping size if, say, 1mm sheets were used. The details of this work can be found in the reproduction of the author's papers at the end of this thesis. Other features of this experiment included:

- Conformal cooling channels.
- Finishing the tool using SLA-EDM electrodes.
- Spark Eroding the two halves of the tool together to form the parting line.

It was hoped that using 0.5mm thick sheet would give reasonable definition and minimise stepping on the assembled test mould but most of the roughness caused on the surface of the tool was due to inaccuracies in the laser cutting process employed at that time.

The finished tools were run on a small injection-moulding rig and neither tool showed any sign of wear over the duration of the run. This was interesting, particularly in the un-bonded laminate tool which had some tall and narrow up-stand features. These were expected to permanently deform through the ingress of pressurised polymer between the laminates at the ends of these features. Figure 3.14 shows the finished injection-mould tool.

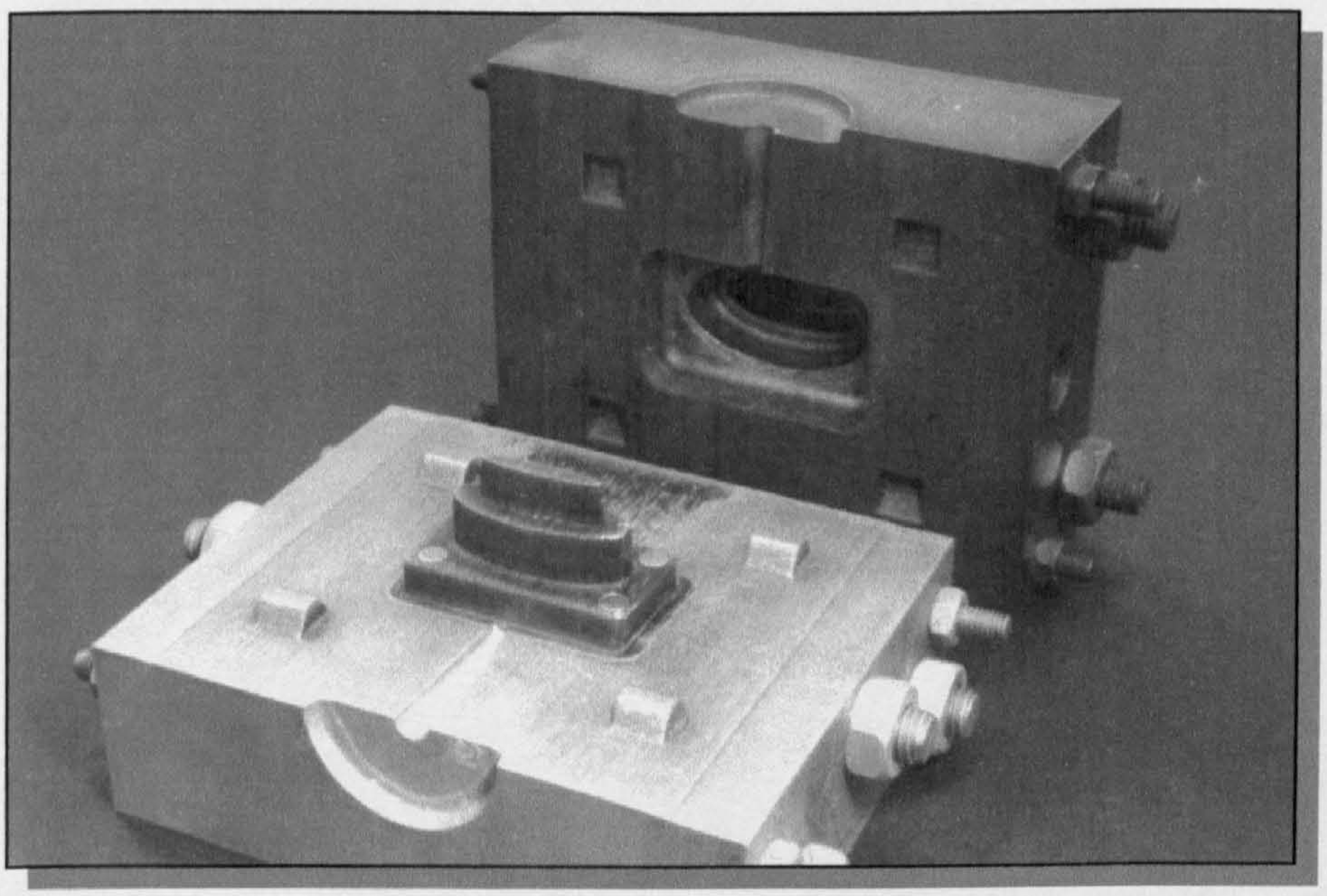


Figure 3.14 The finished laminate injection mould tool

The most recent research to be published into the potential for large-scale laminate tooling for injection moulding has been by CRIF in Belgium. Their work has been extensive in this field and began in 1992 as a Brite Euram Rapitool research program in conjunction with leading industrial companies in this field, Dormal *et al* (1998).

They called the process, for the production of large-scale production laminate tooling for injection moulding, Laser Laminated Cut Cavities (LLCC). The test parts were engine cowlings requiring a tool of at least 500x500x500mm, which eliminated all alternative Rapid Tooling processes from consideration.

The sheet was 1mm thick and the laser cut laminates were stacked vertically for maximum detail on the surface of the tool. The laminates were bonded with an epoxy resin and contained within a metal bolster. No secondary finishing was required and the whole tool, weighing over 1200kg was mounted on a 350-tonne injection-moulding machine. The moulding material was glass reinforced PBTP and the tool was run 150 shots with a later run of 100 shots with no tool degradation.

The final group involved in the development of this field has made some of the most important contributions, not only to injection moulding but many applications for laminate tooling. The process has the name Stratoconception® and relates to the production of laminate tooling for any application that they are asked to look into, Lyett & Barlier (1995).

Their work began in 1990 in France with funding from the Société CHARLYROBOT and is a marriage of multi-axis CNC milling with advanced robotics. As previously mentioned, there are limitations to using CNC milling machines to produce tools due to the shape and size of the cutting head which restricts access into the tool. Their solution was to machine each laminate prior to assembly to form the required tool. This way the tool head is never obstructed, allowing the production of very deep features.

Using a milling head on a 5-axis robot also allows a bevelled cut to be produced on each individual laminate profile. The profiles can subsequently be assembled with none of the stepping which occurs in conventional Laminate Tool. Their approach still suffers the problem of not being able to achieve pure curved surfaces but goes a long way to solving this problem. Muller & Barlier (1995) have recently modified their work to use a laser profiler mounted directly on a robot.

3.3 The Construction of a Laminate Tool

3.3.1 Defining the CAD model

As mentioned previously, the process of building a laminate tool begins with the construction of a suitable CAD model. For the purpose of clarity, the construction of an actual laminate tool produced by the author will be considered. The flow diagram for such an operation is shown in Table 3.1.

When it comes to modelling a tool in CAD, it is normal to start with a CAD representation of the actual part which will ultimately be formed from the tool. It may also be necessary to take account of shrinkage in the moulded material. One of the many benefits of CAD modelling is that the models can be 'scaled' or 'offset' with ease, to compensate for expansion or contraction effects during production.

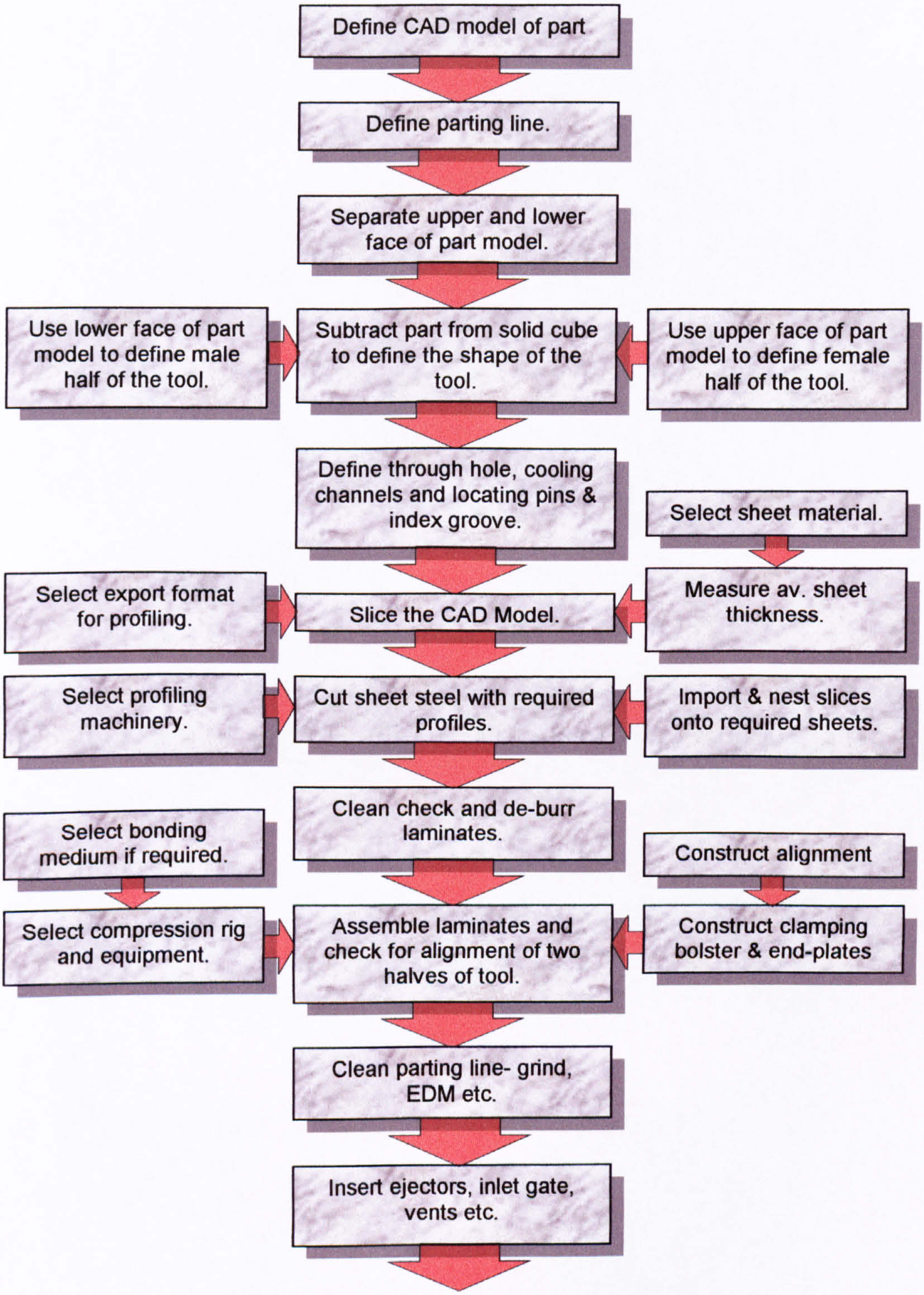


Table 3.1 Flow chart for the construction of a laminate tool

Figure 3.15 shows the CAD model of a polypropylene part which must, ultimately, be produced from the laminate tool.

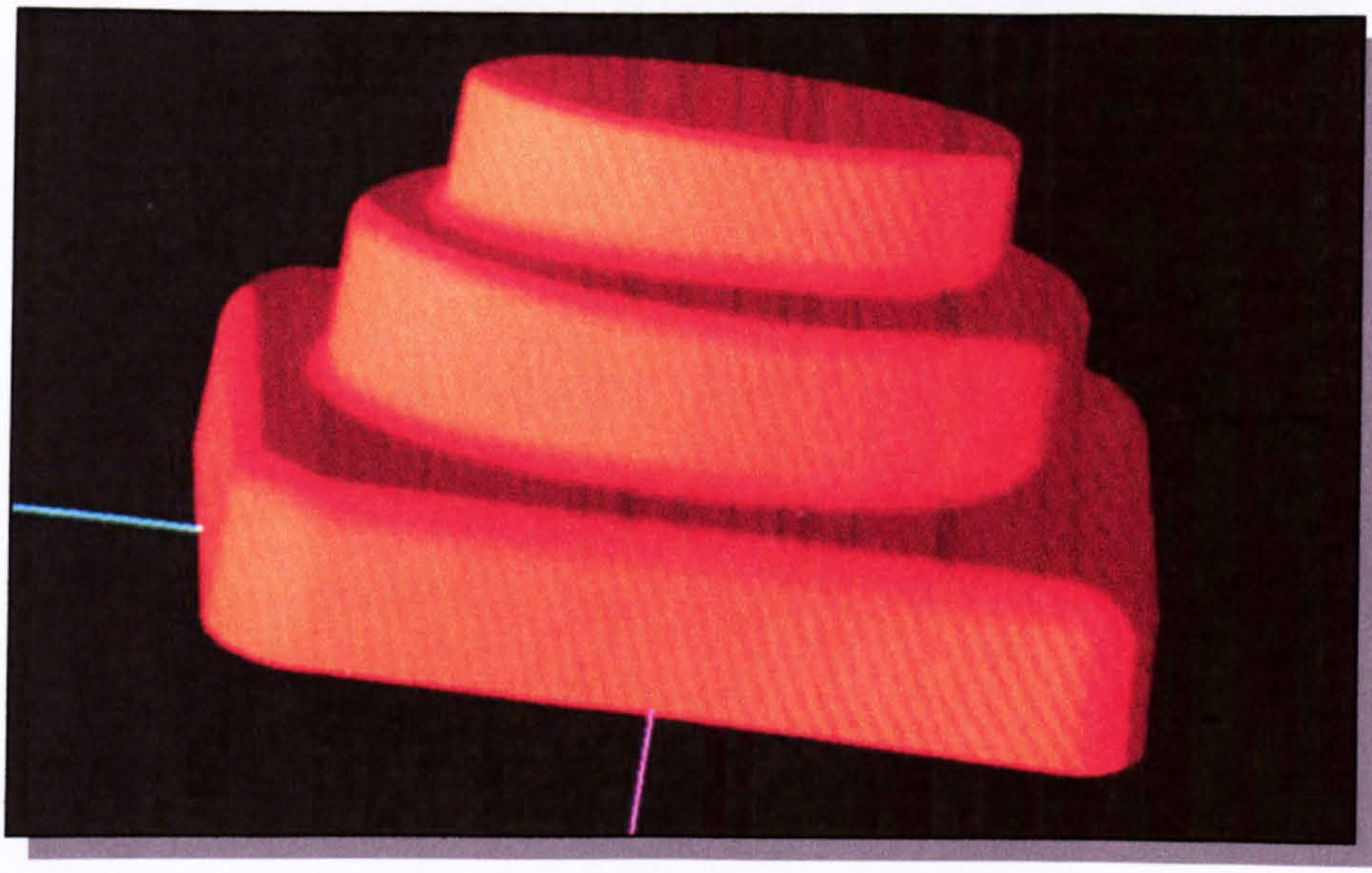


Figure 3.15 CAD model of resultant moulded part

It is then necessary to define the parting line to ensure that once it is formed in the tool, the elements of the tool can be separated to allow the part to be removed with ease as shown in Figure 3.16.

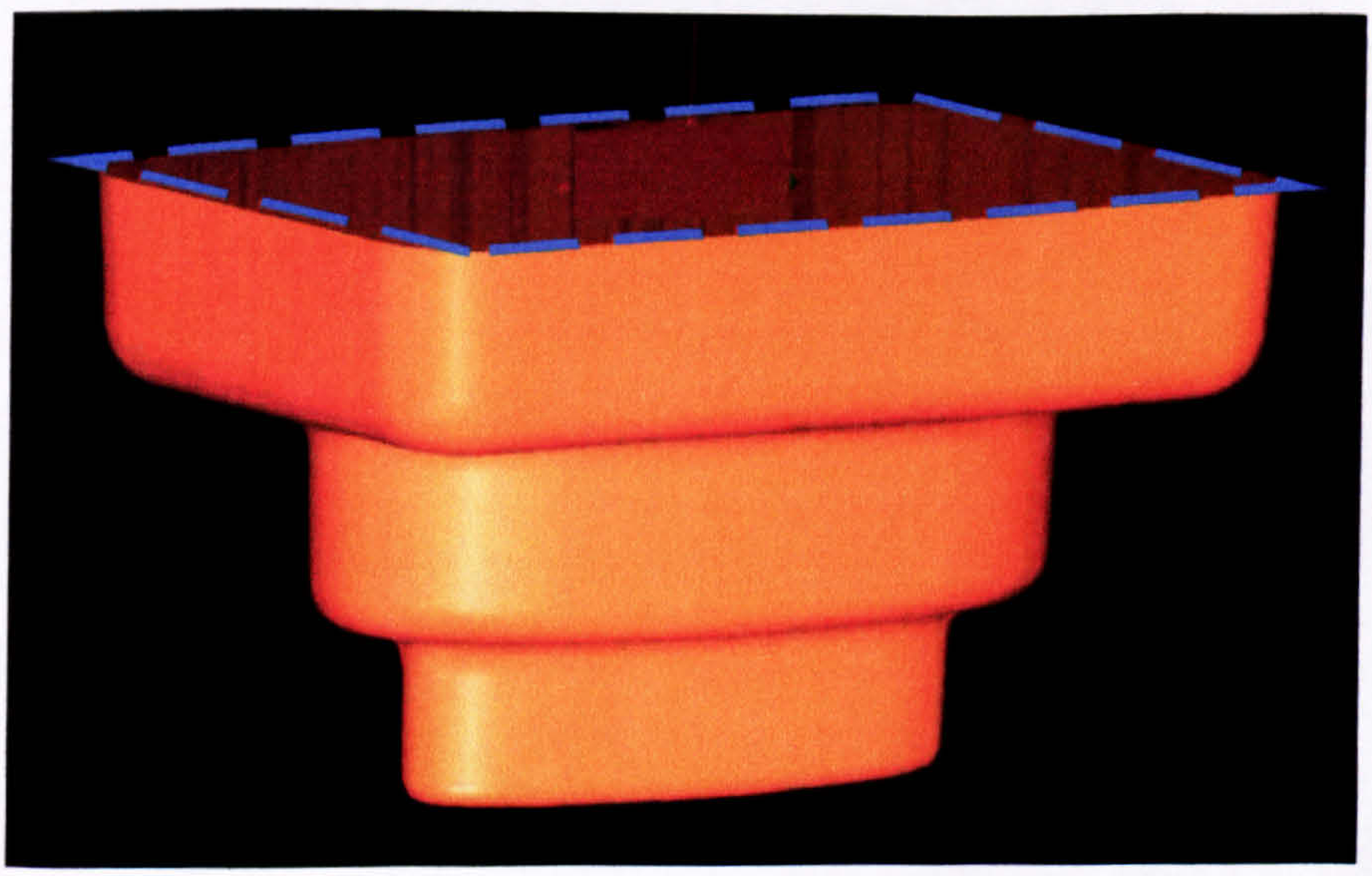


Figure 3.16 Parting plane defined on CAD model

Issues such as undercuts, draft angles and shrinkage of the part onto up-stand elements within the tool must be identified at this stage. Modern tooling can be extraordinarily complicated where complex shaped parts must be reliably removed from a tool. The key to removal of the part from the tool lies in identifying a parting line on the part at this stage. Parting lines tend to leave a witness mark and this too may be a consideration in its location on the part model. It is fair to say, though, that the designer will always opt for the simplest solution and that is to design the part so that the tool, required to produce it, needs only two halves. The blue dotted line denotes the parting line in Figure 3.16.

The part model must then be considered as having two surfaces, the upper and lower. The model in Figure 3.15 has a wall thickness of 3mm and is, therefore, hollow. The upper surface (visible in Figure 3.15) is that surface that will, ultimately, form the female half of the tool and the lower surface (not visible) will form the male half of the die.

Defining the model for the female half of the tool consists of defining a solid cube, larger than the part, and then using a subtraction function to form the shape of the upper face within the solid cube. It must be remembered that the parting line on the upper face must not descend below the surface of the cube. Figure 3.17 shows the CAD representation of the female half of the tool (for this example we will not consider any offsets through shrinkage)

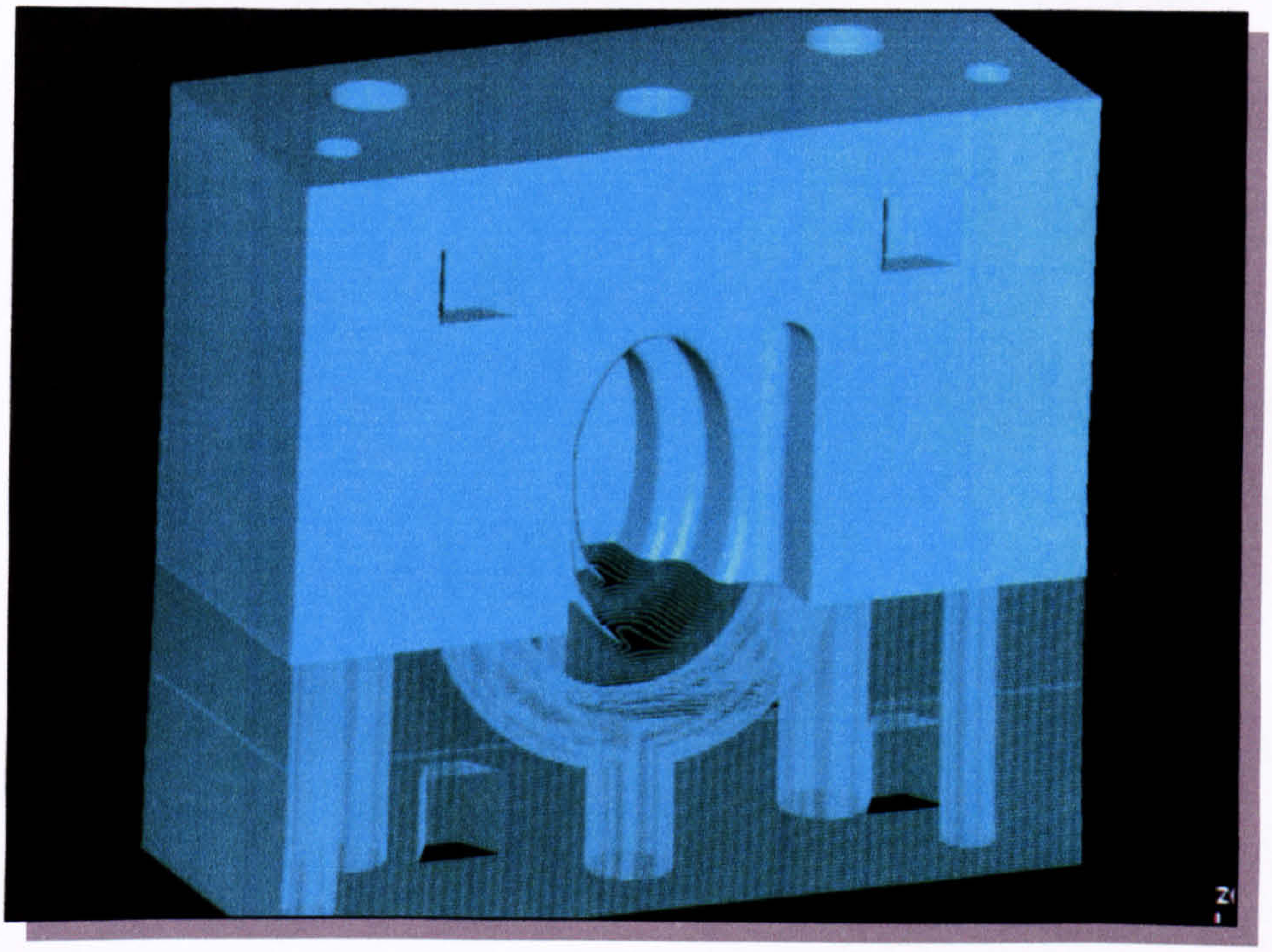


Figure 3.17 Representation of the female half of the tool

This cube now contains the negative impression of the female half of the tool. The same process is then repeated to produce the male half of the tool using the lower surface defined from the part model and adding it to an identical solid block. The two halves of the tool are now defined. It is now necessary to define those features which are necessary for a laminate tool. These features can also be seen in Figure 3.17 and include:

- Through-holes, running the length of the tool, which are ultimately used to pass bolts through to clamp the laminates together in the finished tool.

- Cooling channels, to aid the removal of excessive heat within the tool. A feature of Rapid Tooling is the ability to define cooling channels that conform to the surface of the tool, thus minimising 'hot spots'. On Figure 3.16 this is shown as the elliptical torus in the lower half of the model.

- Locating pins on the parting plane to ensure accurate alignment during moulding. In Figure 3.16 they are shown as recesses and these conform to protrusions on the male half of the tool.

- An indexing groove down one face of each half of the tool. This runs diagonally from the upper front corner of one face of the tool to the lower end of the same face. Laminates will come off the profiling machine in a random order and their location in the assembly must be known in respect to their neighbouring laminates (the alternative is to number each DXF slice so that the profiling machine reproduces the location number on each laminate).

3.3.2 Slicing the CAD Model

With these features defined, the tool model can be sliced to generate the 2D data necessary. The solid modelling package (EDS Unigraphics) allowed the slices to be defined as offset planes through the model. This was done as an automatic subroutine which would take each slice through the model and save it as a separate DXF file.

On Figure 3.17 the parallel lines on the lower half of the tool represent each tool path for each sheet of steel that made up the laminate tool.

The final, and most important, factor in the slicing operation is knowing the thickness of the sheet steel which will be cut to form the laminate tool. Selection of sheet material will be covered in more detail in Chapter Five but, for the moment, it must be realised that if the thickness of the sheet material is greater than the offset thickness, defined for each sheet on the CAD model, then the laminate tool will be elongated upon assembly.

It is critical to study and determine the exact 'mean' thickness for a batch of sheet steel. This varies dependant on such factors as:

- Whether the sheet is hot or cold rolled
- How difficult the material is to roll
- The type of rolling method used
- The direction in which rolling has taken place
- Whether scale is left on the sheet during rolling
- Any post treatment of the sheet which may affect dimensions.

As a guide, tolerances are plus or minus 0.1mm for a batch of 1mm thick steel. It should be noted that, in this example, the model was sliced perpendicular to the parting line.

3.3.3 Cutting the Laminates

Cutting the sheet steel is now a matter of preference. Only a few years ago this was one of the stumbling blocks in the development of this technology. The few techniques which were available tended to be cumbersome and suffer from inaccuracy. The last decade has seen some important changes. Both plasma and laser cutters were generally only used for repetitive tasks (i.e. one profile is duplicated over thousands of parts). The major changes came through computer control which only recently, has allowed many different profiles to be produced using the same cutter.

Software now allows for the import of different cutting profiles (normally through DXF format) which can then be nested onto a representation of the sheet to be cut. This optimises the material usage and can save money by grouping customer orders if the same sheet material is required. The cost of profiling has remained reasonably constant in the last decade but its flexibility and productivity have soared which has resulted in opening up completely new opportunities such as Laminate Tooling. Profiling machine options now include High Definition Plasma, Abrasive Water-jet diameters of 0.1mm, CO_2 and ND-YAG lasers. In addition, the abundance of profiling contractors has made the production of large numbers (commonly over 1000 laminates for a laminate tool) of laminates, each with a different profile, cost effective.

Cutting the laminates for a typical tool requires importing all the DXF files for each laminate, superimposing them onto a CAD representation of the sheet steel to be used and then using a nesting subroutine to fit the laminates onto the sheet to minimise wastage. The properties of the sheet and its thickness are also inputted into the software so that the cutting parameters for the profiling tool can be established. The software then generates a sheet profile which is fed to the profiling tool. Using a laser to cut over a thousand profiles is a matter of a couple of hours programming, and dependant on each profiles size, approximately three to four hours cutting.

As standard, most contractors will finish the laminates to remove any burrs from the cutting process (some of the most recent lasers produce almost no burring) normally by tumbling in a mildly abrasive media and de-greaser (household washing powder). This is an excellent process which not only cleans off burrs but also removes scale, oil and grime from the laminates leaving them in a condition ready for immediate assembly.

3.3.4 Assembly of the Laminate Tool

The first task in the assembly of the tool is to index the laminates. Figure 3.18, shows the laminates to the male half of the tool mounted on a jig:

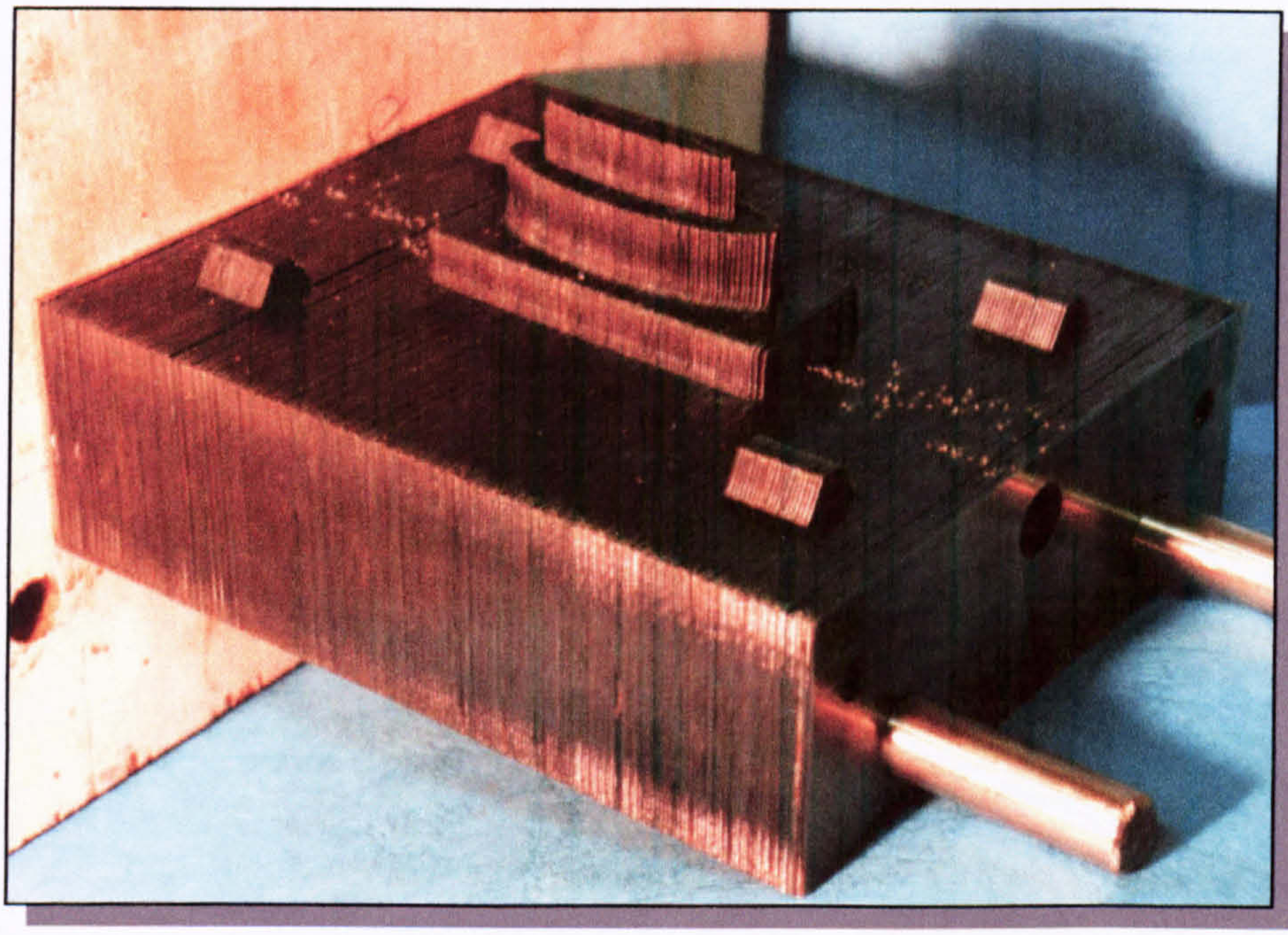


Figure 3.18 Laminates to male half of the tool prior to clamping

The indexing groove cannot be seen on this photograph but, at this stage, it is critical to establish whether laminates are missing or whether any have been cut inaccurately. If they have, this stage quickly shows any discrepancies.

One further consideration in the cutting process can be seen in Figure 3.18. A small burr is commonly left where the laser starts and ends its cut and this can be seen as a collection of lumps on the parting plane of the tool. It is important that these lumps be positioned on the parting plane of the tool as it is this plane which will be finished to ensure clean mating of male and female tool. Where the laminates protrude into the mould cavity, it is important to position the point at which the laser starts and ends to one side of the moulding feature. This cannot be seen on Figure 3.18 as they are on the far side of the tool.

With the laminates indexed and checked for cleanliness, they can then be clamped together. This is one area where mistakes can happen. Laminates are never perfectly flat and there are always minute differences in the thickness across the profile. Though hardly noticeable in a few laminates, where 1000+ laminates make up the tool the differences can become exaggerated.

To explain this, it is easier to imagine a laminate stack as a spring. Most rolling processes will impart some stress into a sheet and cutting the sheet into smaller profiles will release these forces. The result is that individual profiles will warp slightly. For this reason, above all others, the laminates must be constrained in such a way that they are kept square to each other and then compressed.

Simply bolting the laminates together through the pre-defined through-holes will result in the laminates deforming where the bolts pass through the stack. For this reason some form of plate must be used to ensure an even compression across the cross-section of the laminate stack. In Figure 3.19, it can be seen that, in this case, two end-plates were employed for each half of the tool.

One further point is where the very small differences in sheet thickness can leave one half of the tool slightly longer than the other, even though equal clamping pressures are applied to both halves. Applying slightly more compression can overcome this to ensure the two halves of the tool align.

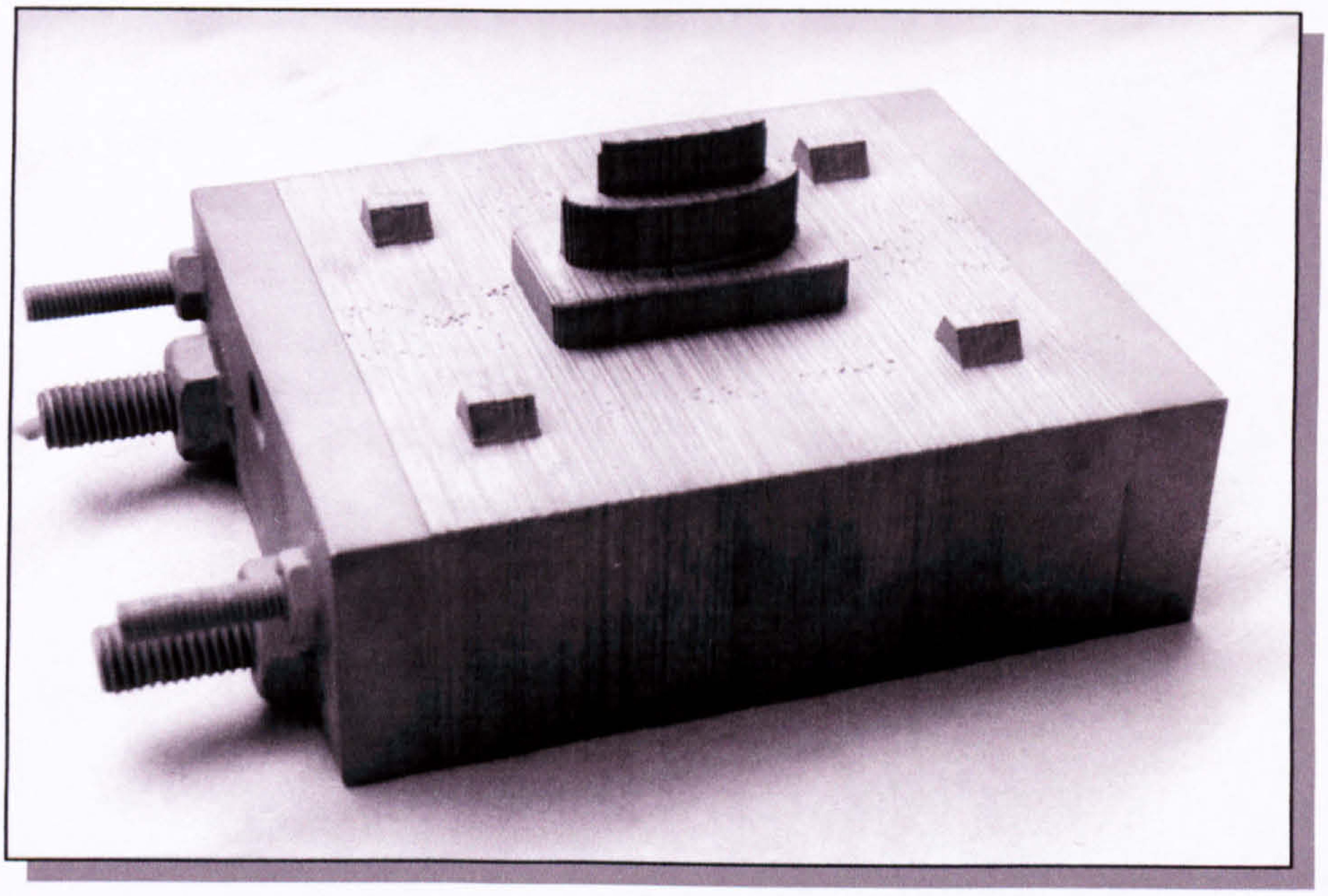


Figure 3.19 Male half of the tool showing clamping plates

3.3.5 Finishing the Laminate Tool

Three final operations still remain to complete the tool. The first is to ensure that the two halves of the tool mate cleanly at the parting line. There are numerous established methods for doing this and one popular technique is to Electro-Discharge Machine (EDM) the two halves of the tool together. This is favoured over grinding both faces, as grinding can remove too much material from the parting plane and therefore affect the thickness of the moulding. Using EDM allows for the imperfections in the parting plane to remain, whilst ensuring a complete seal between the male and female halves of the tool. The limitations with this technique lie in the size of the tool being made. To EDM the tool, it must be submerged completely in dialectic fluid (using EDM also ensures that the locating pins align accurately).

The second operation is to cut in the inlet gate for whatever material is being moulded. How the gate is orientated is mainly dependent on the moulding equipment being used. Figure 3.20 shows the inlet gate in the foreground.

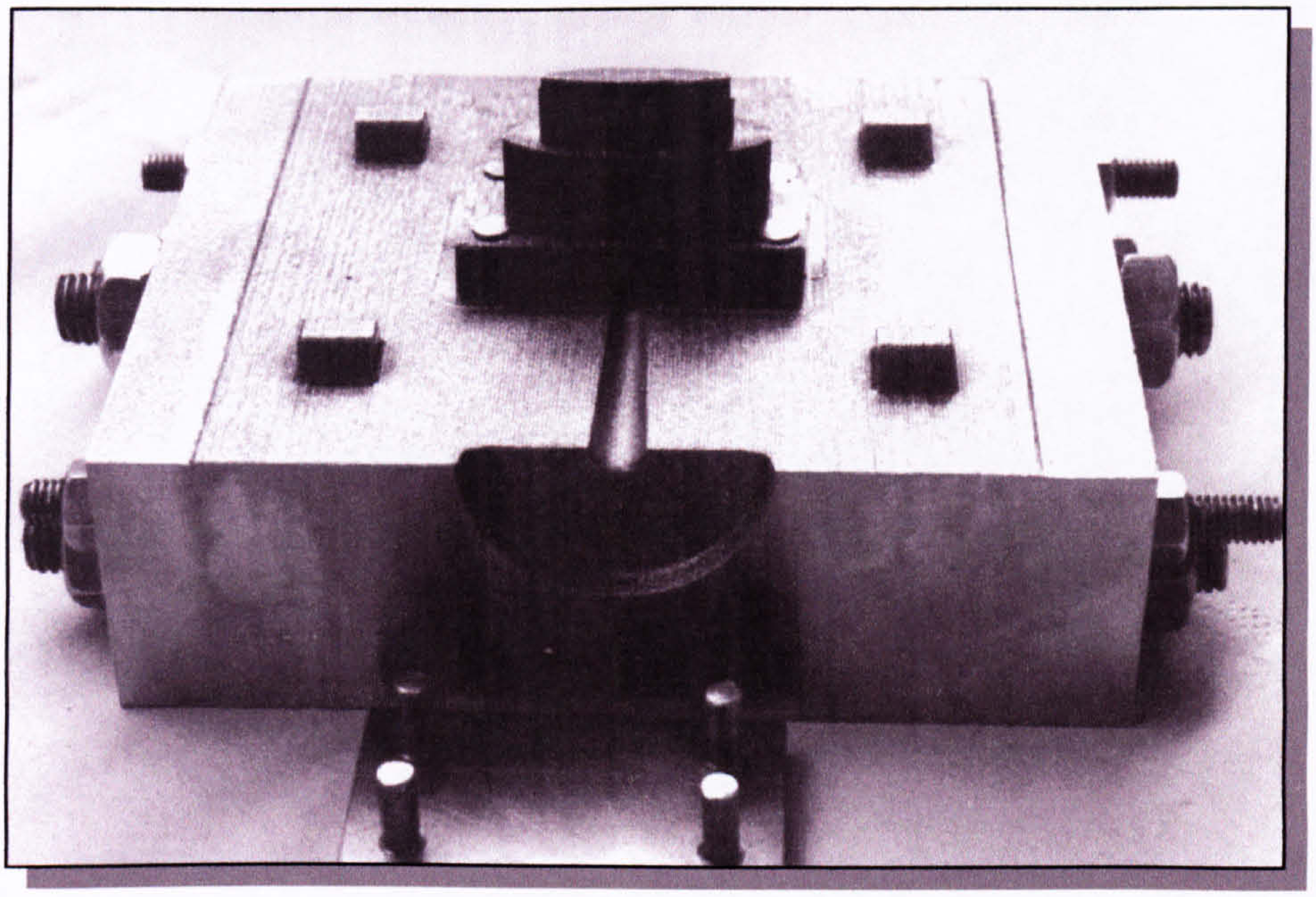


Figure 3.20 One half of the completed laminate tool

This was created by clamping both halves of the tool together and using copper EDM electrodes to form the inlet gate feature. Drilling through stacks of laminates can be problematic as the pressures imparted by the drill tip can force laminates apart (if clamping pressures are insufficient) and leave swarf in the gap, thus distorting the stack.

The final operation is the inclusion of ejectors, should they be required. Again, these should not be drilled due to the risk of distortion and, again, EDM is an ideal process to ensure clean ejection of the moulded part. The finished tool has already been discussed and shown previously in this chapter. Figure 3.21 shows one of the many polypropylene parts successfully produced from this tool.

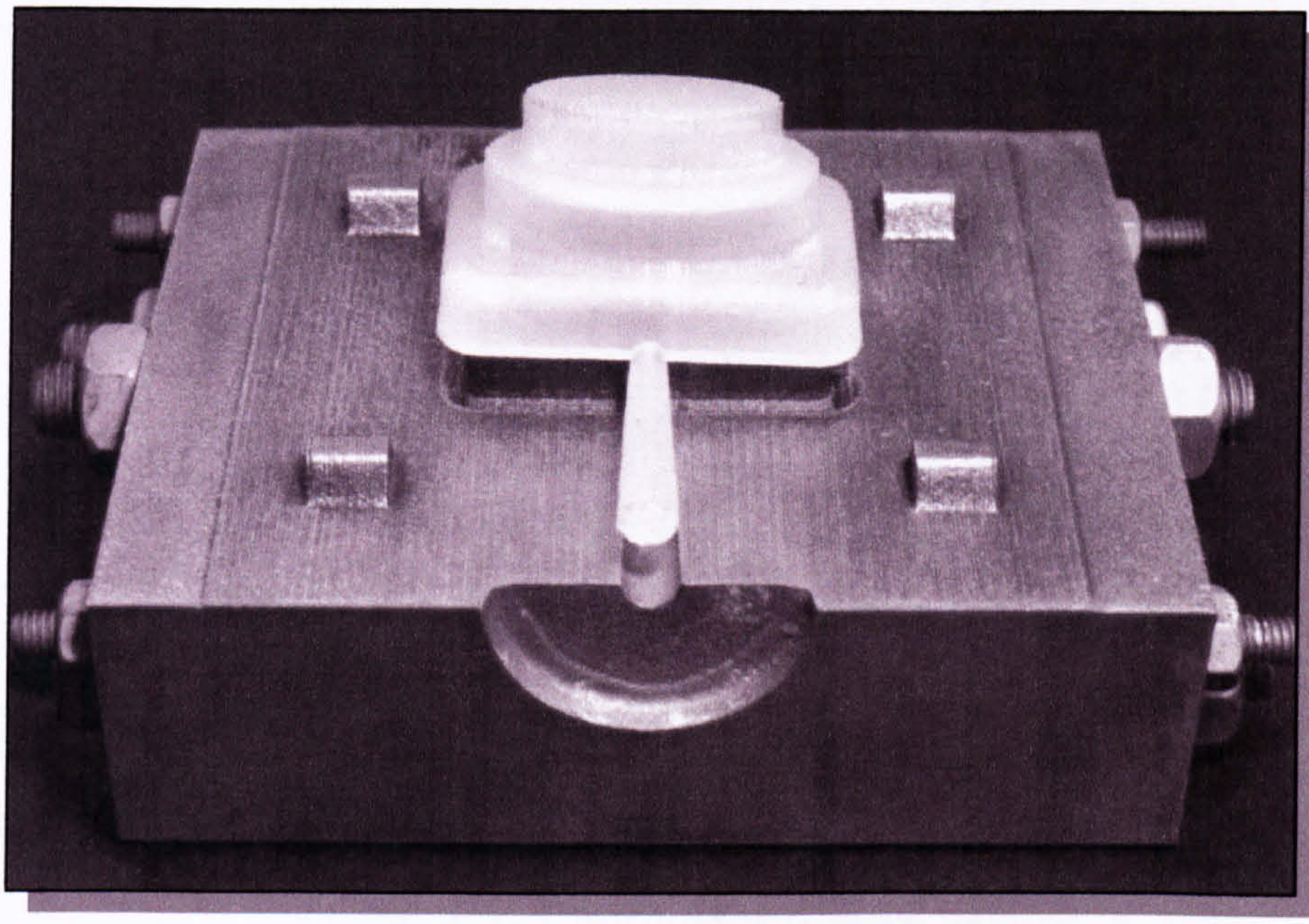


Figure 3.21 Polypropylene moulding from laminate tool

There are many further issues which relate specifically to the design and production of Laminate Tooling. A few have been highlighted here (Laminate orientation, clamping, warping etc.) and more will be discussed in the following chapters.

3.3.6 Advantages of Laminate Tooling

From the points highlighted in this chapter, it is clear that there are a variety of benefits to be gained with Laminate Tooling over conventional tooling machined from solid billets. These vary, dependant on the application, but a few stand out as generic to this technology. These advantages can be summarised as:

- Laminate Tooling is scaleable. Tool size is only limited by the maximum sheet size which can fit on a profiling tool bed.

- From CAD design to assembled tool in a matter of days. Cutting speeds are typically a 1mm thick sheet every 2-3 minutes.

- Laminate Tooling allows for the inclusion of deep, narrow internal features within a tool that a milling head cannot reach into.

- For volumes over 500×500×500mm, sheet steel is less expensive than billet.

- There is a shorter lead-time for the production of the same volume of sheet steel as for billet, as it can be purchased 'off-the-shelf'.

- Modern rolling techniques can impart a finer grain structure to the sheet than is possible from cast and forged blocks.

- Complex internal features can be modelled and produced in the tool such as Conformal Cooling Channels.

- The range and variety of sheet material is much greater, this may involve a different thickness of sheet in the same tool or different sheet material in the same tool.
- The concept of low cost tooling allows manufacturers to consider short production runs to maintain a competitive edge.

- Sections and internal features within a Laminate Tool can be replaced or modified through the exchange of laminates.

3.3.7 Current Status of Laminate Tooling

Tromans and Wimpenny (1995) highlight the future of Rapid Tooling lying with the development of Laminate Tooling, 3D printing and Laser Sintering/Fusion. There are currently five University research groups in the UK looking into Laminate Tooling. The first, Dundee University, has been exploring this area from the standpoint of bevelled laser cutting of sheet steel.

The second and third are Warwick and Leeds Universities who are modifying the LOM process to lay down and laser cut thin layers of metal foil, as well as address the problems of bonding the laminates in a stack, as part of a European funded project (Adams and Wimpenny, 1998[1]). The final group is the Rapid Manufacturing Group at De Montfort of which the author is a member.

Laminate Tooling research has moved on fast within the Rapid Manufacturing Group over the past five years. Up to the start of this project, the group have explored laminate tooling for foam casting, thermoforming and injection moulding as well as addressing issues such as replaceable inserts, laminate bonding, clamping, material selection and finishing. Details can be found in the author's papers reproduced at the end of this thesis.

Chapter 4: Die-Casting and Pressure Die-Casting

4.1 Introduction

The terms die-casting and pressure die-casting are used interchangeably within the industry. There are important differences, however, which affect the direction of this research and it is, therefore, necessary to form the distinction between the two.

Die-casting is the generic term used to describe a series of metal casting processes which includes pressure die-casting. Clegg (1991) defines die-casting as *"a process that employs a permanent, reusable mould or die, generally made of metal"* whereas Street (1986) defines pressure die-casting as *"a process in which molten metal is injected into a precisely dimensioned steel mould"*. Both definitions use a metal mould but the latter employs some form of pressurised injection system to move molten alloy into a precisely dimensioned metal mould. Pressure die-casting evolved out of die-casting so an explanation of the process must begin with the development of die-casting.

The key element in the die-casting process is the use of the 'permanent mould'. Up until its conception, all casting processes were based on the concept of an 'expendable mould' into which metal was cast. As its name implies, 'expendable moulding' involves the production of a one-off mould into which metals are cast and the mould destroyed to remove the casting.

Many variations exist for this process, the main ones being; sand-casting (bonded or un-bonded), ceramic or plaster moulding and investment casting. Each achieves its objective by eliminating wastage of metal over the alternative that is to machine the part from a solid billet. Die-casting has not superseded the 'expendable moulding' processes, but merely enhanced a procedure which achieves 'Near Net Shape'. Near Net Shape is the term used to describe a forming process which achieves as close to the desired final shape of the part or product in one step.

This is a loose definition, as most casting processes produce parts which require finishing, some more than others. For example, sand casting has been in use for millennia but gives a relatively rough surface finish due to the coarse texture of the sand which makes up the mould. Investment casting, on the other hand, can reproduce very fine detail from the pattern used to generate it primarily due to the fine texture of the ceramic used to form the shell into which metal is cast.

Die-casting takes the benefits of investment casting one stage further. Die-cast dies can be produced with a near mirror surface finish and it is this detail which dictates the finish on the casting. More importantly, die-casting allows the production of more than one casting from the one die.

Die-casting dies are designed to produce thousands, and sometimes millions, of castings before the die wears out. In many cases, the castings which emerge from die-casting dies rarely require any finishing, except for the removal of the runners (note there are no risers).

4.2 Background to Die Casting

The motivation behind modern die-casting, and its associated technologies, came about through the need for greater numbers of identical parts, even though die-casting can be traced back as far as the Bronze Age (Upton, 1982) with the use of simple stone moulds for the production of bronze axe and spearheads.

Modern die-casting has its roots at the beginning of this century. In its simplest form, it began with the production of simple permanent cast iron or steel moulds into which various metals of a lower melting point than the mould could be poured (e.g. lead-tin alloys for the production of printer's type). This technique is known as 'Gravity casting' and relies on similar design principles to the expendable moulding processes.

Gravity casting is still used extensively, as it requires little equipment. The only real investment is in the production of the metal die which is used. Gravity casting has its limitations though; the concept of a permanent mould is to increase the quantities of castings from the one die and the key to this is the time taken to fill the die with material and eject the solidified part from the die before the next shot begins. To achieve this would require some lateral thinking as well as some form of impetus which would drive the need for greater mass production. This impetus was undoubtedly two World Wars and the staggering growth of the consumer market.

Die-casting was a natural choice for the early automotive manufacturers, who required the mass production of intricate parts such as connecting rods and bearing casements. To machine each part from billet was time consuming and wasteful, but at the turn of the century there were very few metals which could be die-cast to give robust enough parts for use in applications such as components for the engine of a vehicle.

4.2.1 Zinc Alloys

Zinc Alloy was the first material to achieve true mass production status in the automotive industry, though it was not without its flaws. The first alloys to be manufactured for die-casting suffered from intercrystalline corrosion, due to the use of lead and cadmium as the alloying agents. This resulted in embrittlement, due to the growth of large crystals upon cooling, which were easily sheered upon impact. This embrittlement was also exacerbated by the reaction with oxygen in the atmosphere around the furnace.

There were two solutions to this problem. The first was to contain the zinc alloy in a furnace with a controlled atmosphere which was physically attached to the machine which held the die blocks. This allowed the zinc alloy to enter the die cavity without coming into contact with the atmosphere. The second solution was to deliver the alloy into the die cavity under pressure to give a finer grain size to the casting.

The use of pressure to move the zinc alloy into the die cavity was a major leap forward and sparked off a series of new technologies which will be covered in the next section. Zinc die-casting is still extensively used for parts as diverse as aesthetic mouldings such as door handles and some load bearing applications such as pump housings, pulleys and many peripheral parts which go into the construction of an engine. Zinc alloy has its limitations - it can't be used for structural parts of the engine such as the engine block or gearbox housings. For most of the early part of this century, steel and cast iron were the champions for these high stress applications.

This situation was to suddenly change in the 1970's when the Energy Crisis struck. The sudden realisation that the world's oil reserves were under threat made governments force automotive manufacturers to look for lighter materials to replace those parts traditionally produced from steel, in the attempt to reduce fuel consumption.

4.2.2 Aluminium Alloy

The first candidate for a substitute for steel castings was aluminium. Aluminium had always been a costly material due to the huge amounts of energy required to separate it from the Bauxite in which it naturally occurs. Street (1986) estimates 40 megawatts of power is required to refine each tonne of aluminium. The key to reducing the cost of aluminium was in recycling it. The Aluminium Association (1999) states that secondary (recycled) aluminium requires only 5% of the energy required to produce primary aluminium. To date, 60–70% of all automotive aluminium is sourced from recycled metal. This practice brought the cost of aluminium down to the point that it could be considered for die-casting.

The Aluminium Association (1999) note that aluminium is one-third the density of steel. It is now used in parts as diverse as engine blocks, transmission housings, drive shafts, wheels etc.

The second hurdle to die-casting aluminium was the material itself. Aluminium alloys have a melting point of approximately $695^{0}C$ (dependant on the alloying element), compared to zinc at approximately $450^{0}C$. Where zinc is used in steel dies, the lower melting point has little effect on the die steel itself and lends itself to millions of castings before the die is worn out. The higher temperatures of aluminium alloys present their own unique problems. At these elevated temperatures, die steels can begin to anneal and the rapid heating and cooling during casting can lead to thermal shock and fatigue (heat checking). In addition, molten aluminium is corrosive to steel and will solder itself to the die in unfavourable conditions. There are also issues relating to the delivery of the molten alloy to the die cavity which will be covered later in this chapter.

In the techniques covered in the next section, it will be shown that there is only one process, at present, which can deliver the aluminium alloy into a steel die and, even then, the furnace atmosphere must be carefully controlled to prevent hydrogen embrittlement that greatly reduces its performance.

4.2.3 Magnesium Alloy

The second candidate identified as a substitute for steel in automotive parts was magnesium alloy. As an engineering material, magnesium alloys are even more attractive than aluminium alloys. They possess a lower melting point (approximately 650^0C) than aluminium alloys, a density less than aluminium, and Brace and Allen (1957) note that, where pressure die-casting is employed, injection speeds can be 1½ times faster with magnesium casting than aluminium and all this with the strength of steel.

As with all materials, there are specific problems unique to magnesium alloys. The problem comes at the casting stage. When the material is molten it will attempt to oxidise under pressure, as do all molten metals. The key to developing magnesium die-casting has been to control the furnace, die-casting atmosphere and alloy temperature.

As with the introduction of all new die-casting materials, magnesium alloy bought about its own equipment requirements. Magnesium is still an expensive commodity compared with aluminium and, particularly steel, but again this market is being driven by factors other than the cost of the raw material. Portable electronics are rapidly becoming the force behind this change. Consumers want strength with low weight and low weight opens up new markets for magnesium.

Magnesium alloy is rapidly increasing in use and will almost certainly increase in its market share through the millennium. Even so, this fear of explosion (though exaggerated at the time) resulted in aluminium being the choice of the automotive industry at the time of the energy crisis.

Zinc, aluminium and magnesium alloys make up the vast majority of the pressure die-casting industry and consumption figures will be discussed later in this chapter. Tin and lead are rarely considered as casting alloys in the modern foundry. Various processes now exist to deliver these alloys, under pressure, to permanent moulds or dies and this thesis is primarily concerned with those permanent moulding processes which utilise pressure to reduce the cycle time between shots. Within the area of pressurised die-casting there are essentially three categories:

- High Pressure Die-casting (HPDC)
- Low Pressure Die-casting (LPDC)
- Squeeze Forming and Semi Solid Metals (SSM)

Though each process differs from the next, there are elements that unite them, these are:

- All are methods for forming metal parts, typically aluminium, zinc, magnesium and to a lesser degree lead, tin, brass and, currently, steel.
- All require the production of re-useable steel moulds capable of producing tens of thousands of castings, sometimes millions.
- All produce near net shape castings which require little or no finishing.
- All work at elevated temperatures due to the melting point of the material being cast.
- Most rely on extreme pressures (>200MPa), not only to hold the elements of the die together but also to increase the cycle times by forcing the casting material in to the desired shape.

4.3 High Pressure Die Casting (HPDC)

High pressure die-casting (HPDC), in its simplest form, attempts to speed up the die-casting process significantly over all other casting processes. It is the fastest metal casting process capable of generating a finished part requiring little or no finishing in a matter of seconds. The cost of equipment may be high but, where large quantities of product are required, it is the cheapest production method when dividing the cost over the castings produced.

Forcing metal into a steel cavity also creates benefits over the gravity casting process. The speed of the cycle gives little time for the molten alloy to oxidise. During transfer from the holding furnace to the die-casting machine pressurisation of the molten alloy results in a much finer grain size to the part over gravity casting. The use of pressure also increases the fluidity of the molten alloy allowing it to flow into, and fill, far finer detail within the die than gravity casting is capable of.

4.3.1 Component Parts of the HPDC Machine

As in all pressurised permanent moulding processes, high pressure die-casting (HPDC) utilises a steel die. The die will always be constructed of more than one section so that it can be opened after the casting cycle to remove the part.

The die is mounted in a frame which consists of hydraulic rams which hold the sections of the die permanently closed during the casting cycle. The hydraulic rams must, not only, hold the die closed during casting but also withstand the pressure of the molten alloy being forced into the die which tries to force the sections of the die apart. Die-casting machines which are used to cast engine blocks, for example, typically have a closing force on the die of some 3,000 tonnes.

Even though there are a variety of die-casting machine manufacturers around the world, they all produce machines based on the same design principle shown in Figure 4.1. With most HPDC machines, the die will be constructed in such a way that it consists of two halves.

The die is mounted in such a way that the parting line for the die runs vertically. The die itself is clamped to two large metal platens. It is not enough to simply mount the two halves of the die to the end of a hydraulic ram, as the pressures involved to hold the dies closed would deform them. The platens are, therefore, used to spread the high loads over the entire surface of the die as well as provide a suitable platform to mount the die to and change dies when required.

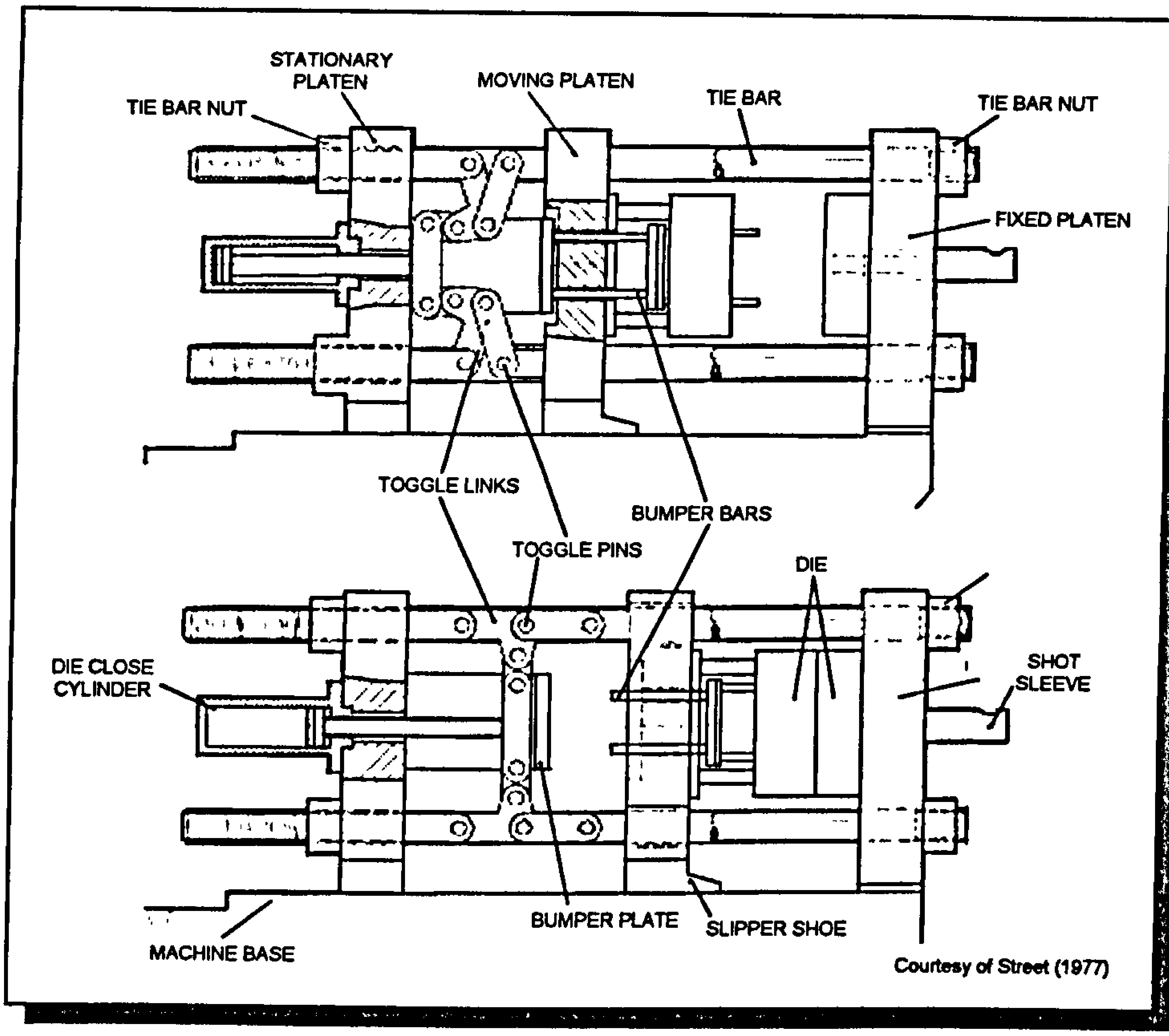


Figure 4.1 Schematic for a HPDC machine

There are three platens which make up a typical machine. Two are fixed, at either end of the machine, and are connected by four sturdy tie bars which hold the entire frame rigid. In between the two fixed platens is a third platen which is moveable along the length of the tie bars.

Of the two halves of the die, one half (usually the female half of a tool) is attached to the fixed platen and this half is called the 'cover die'. The other half of the die is attached to the moving platen. This ensures that the die can be opened and closed with a very high degree of precision. The two halves of the die must always meet precisely for each casting, as misalignment will show up on the casting as a witness mark along the parting line.

As with all casting processes there is some shrinkage as the casting cools, before it is removed from the die. This causes the casting to shrink onto any up-stand detail or feature in the die cavity and will be difficult, if not impossible, to remove unless there is assistance. To ensure that the casting is pushed off, the die will contain ejector pins.

The ejector pins rest flush with the face of the die cavity during casting and pass through the moving platen to a second hydraulic ram at its rear. Once the casting cycle is complete, the moving die opens and the ejector pins are pushed forward. These act on the underside of the, now solid, casting and force it off any features on the male half of the tool. For this reason the die, which is attached to the moving platen, is referred to as the 'ejector die'.

The next features of note on the machine are the tie bars and, more specifically, the tie bar nuts which are locked in place during normal operation. Different dies will be run for different products and, though standardisation is the keyword of the 1990's, different dies, at present, are rarely the same size. To overcome this, the machine must have a mechanism to allow the space between the two working platens to be altered for different dies. The secondary platen is, therefore, moveable. By releasing the tie bar nuts on all four tie bars, the secondary platen may be moved forwards or backwards.

This may not seem logical at first as most people assume that the hydraulic ram (closing cylinder), used to close the die and hold it shut, could be projected forward until the two halves of the die met. This is impossible when you consider the locking forces necessary to keep the die shut. No hydraulic ram can safely hold two halves of the die shut and apply 3,000 tonnes locking pressure. If the hydraulics should fail during the casting process the two halves of the die would be blown apart with devastating consequences. To ensure the dies always remain closed, even if the hydraulic ram (closing cylinder) fails, all machines incorporate a 'toggle mechanism'.

The end of the closing cylinder is not attached directly to the moving platen. In between them is a series of lever arms which allow the closing cylinder to push the moving platen forward to engage the two halves of the die. As the dies engage, the closing cylinder continues to move forward which forces the levered arms on the toggle to 'lock over'. This safely locks the two halves of the die in place but does mean that, for the 'locking out' process to take place, the distance between the working platens must be set exactly to take into account the thickness of the die.

The final element in Figure 4.1 to explain is the molten alloy delivery or injection system and it is at this point that the construction of the machines varies dependant on the type of alloy being cast. There are fundamentally two categories of HPDC:

- Hot Chamber HPDC
- Cold Chamber HPDC

4.3.2 Hot Chamber HPDC

At the beginning of the century, the only material which could be cast in steel dies was zinc alloy. Bronze was considered and tried but the material properties were not capable of making it a substitute for cast steel parts. Zinc is strong, light, and its low melting point had little detrimental affect on the steel dies used to form it. Aluminium and magnesium alloys were unsuitable at this time, primarily due to their higher melting points but also, because their use was restricted due to the poor quality of the die steel which was produced.

Holding zinc at the correct temperature was impeded by the primitive control systems used to hold it at casting temperatures. These temperatures were important as it was necessary to ensure that the zinc held enough heat to keep it fluid as it passed into a cool steel die. As in all casting processes, the alloy had to be 'superheated' (overheated around 30^0C above melting point) to overcome the rapid chilling in a steel die when compared to a sand cast mould. Superheating gives rise to excessive oxidation in the molten alloy if it comes into contact with the atmosphere, so it was important to devise a delivery system to the die that minimised the distance between the two. The answer was to attach the furnace to the die-casting machine itself and take molten zinc alloy directly from the furnace and deliver it, under pressure, into the die. As the injection mechanism was an integral part of the furnace so the process became known as Hot Chamber HPDC. Figure 4.2, is a schematic for such a delivery system.

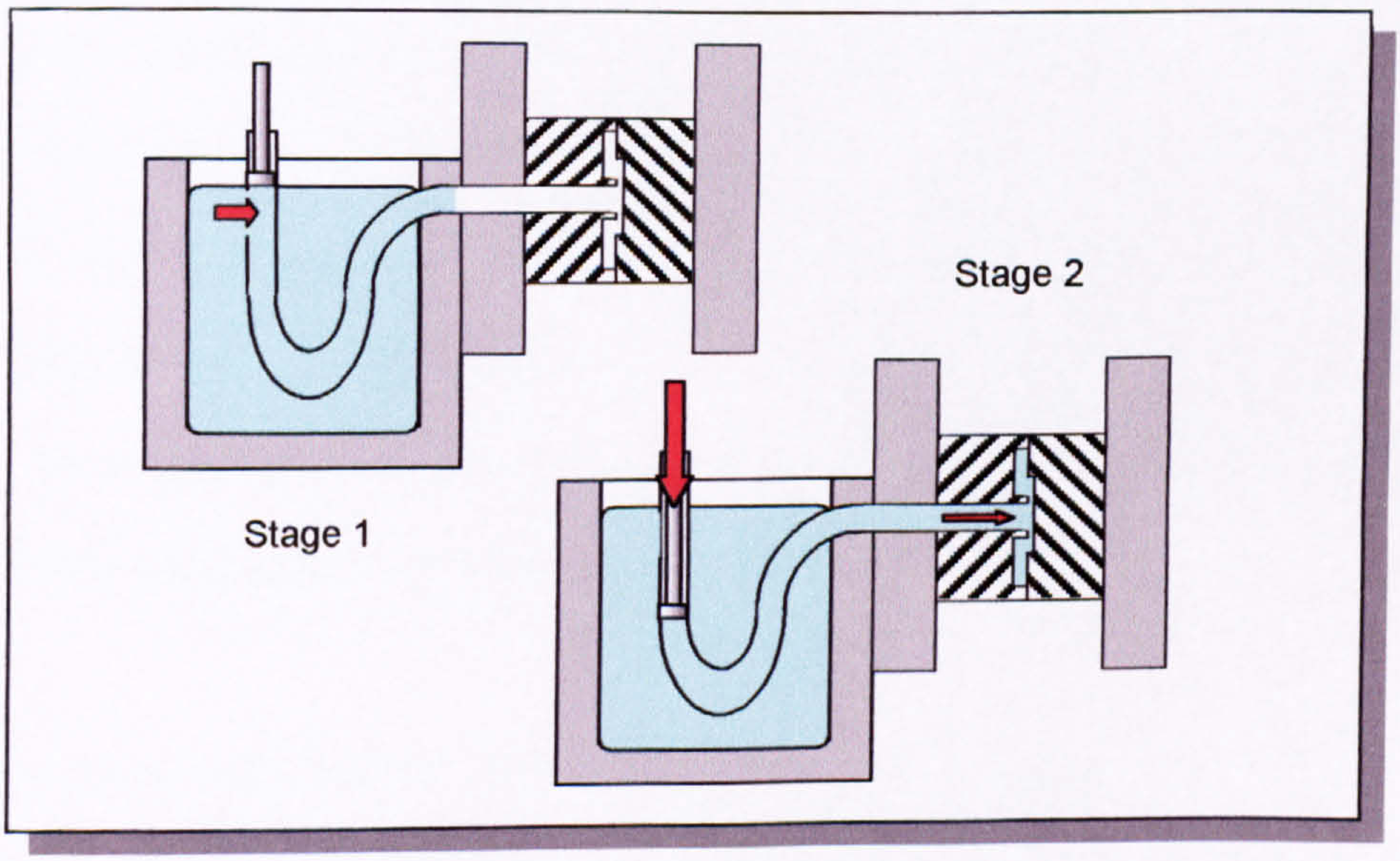


Figure 4.2 Delivery system for hot chamber HPDC machine

By referring back to Figure 4.1, this furnace and plunger unit (not shown) sits behind the fixed platen to the right of the diagram. On injection, alloy passes through a curved 'gooseneck' into an aperture in the centre of the cover die until it meets the parting line and is then deflected through the runners and gates into the relevant die chamber.

The delivery of the 'shot' (a measured amount of molten alloy) is controlled by a hydraulic plunger. Whilst the system is inactive, the piston is fully retracted inside the shot sleeve. In this position, the alloy fills the sleeve and is kept at the correct temperature by the furnace. When the die is closed, the plunger is activated where upon it descends slowly down the shot sleeve until the plunger head seals off the inlet port. At this stage, no more alloy can enter the shot sleeve until the cycle is complete. This is important as it ensures that an exact amount is delivered to the die at each casting.

One of the advantages of all pressure die-casting processes is that there are no risers as in expendable casting processes. In expendable casting processes the mould cavity must always be over filled. The excess material passes through the mould cavity, carrying any dross or impurities picked up from the mould walls which may impair the quality of the casting. This excess rises out of the mould cavity into the 'riser' where it solidifies and is subsequently broken off the casting and discarded. Metal dies are intrinsically cleaner than expendable dies so require no dross collector or riser and so reduce the amount of metal required (a small overflow is sometimes included in the pressure die-cast design if impurities are expected).

As there are no risers in HPDC, the shot volume must be accurately measured to ensure only enough alloy is delivered into the casting. Once the shot is delivered into the die chamber, the shot plunger begins a compaction procedure in which it holds the alloy in the die chamber at an elevated pressure until the alloy has chilled. The reason for doing this is to overcome shrinkage.

Campbell (1991) states that with expendable moulding systems there is approximately 4% shrinkage for certain metals, with aluminium this can be higher still. This means that the mould designer must always take this shrinkage into account during the construction of the mould. This is a difficult task, as thick sections on a casting will shrink more than thin sections. In the development of pressure die-casting, the reduction of shrinkage was a main objective. Shrinkage does still occur, even with today's machines, but it is a fraction of that found in expendable casting processes. The injection plunger, for all pressure die-casting machines, will go through three phases:

- Take Up (1st phase)
- Injection (2nd phase)
- Compaction (3rd phase)

The 1st 'take-up' phase has been covered and is the initial, slow, movement forward of the plunger so that it engages the molten alloy and seals off the inlet port. This stage continues and pushes the 'front' of the molten alloy up through the 'gooseneck' and into the nozzle but not into the die.

With the alloy still moving, the plunger then moves into its 2nd 'injection' phase and the plunger is thrust forward (approximately 10m/s). This motion forces the alloy into the die and fills it completely. The speed of injection is important as it overcomes any premature chilling of the alloy whilst the die is filling, it also acts to force the air out of the die through narrow vents cut into the parting line of the die. This stage may only take around 0.05 to 0.1 of a second depending on the size of the die cavity.

Once filled, 3rd phase 'compaction' is initiated before the alloy can solidify. As the alloy chills it will begin to shrink. With no 3rd phase, the casting would try to shrink away from the walls of the die. By applying a force to the alloy of around 50-70N/mm^2, material is forced into the die cavity to allow the casting to shrink in its centre and not away from the walls of the die. This stage has the added advantage of reducing the size of any inclusions or air pockets which may have been entrained in the alloy during injection.

The 'gooseneck' is designed so that when the die is opened to eject the casting, there is not a plug of solidified alloy left which would prevent the next shot from taking place. Hot chamber machines for zinc alloy casting, rarely go above locking forces of 500 tonnes, most being well under 100 tonnes. They are ideal for the production of many small and intricate parts with dies producing many millions of parts. Compared to other die-casting processes they take up little room and are relatively safe to operate.

4.3.3 Cold Chamber HPDC

Magnesium has been used in the hot chamber process with some success but the process works at pressures too low to ensure adequate compaction during solidification. For aluminium and magnesium alloys the cold chamber process was developed.

The first problem to solve was the quality of the die steels used. The early die steels lacked the homogeneity of modern tool steels. Inclusions, large grain size and forging large billets for dies resulted in premature failure in many early dies. Thermal fatigue and heat checking (cracking in the surface of the die through rapid heating and cooling) forced steel manufacturers to modify their product. This included the addition of alloying agents such as tungsten, vanadium, molybdenum etc, which make steel resistant to the effects of the alloys during cold chamber die-casting.

From the outset, the industry saw the potential of moving away from the small castings associated with hot chamber machines, to machines capable of casting cylinder heads and gearbox housings. Though the machine basically remained the same (though scaled up), it was the delivery system which caused the biggest problem.

Every attempt to incorporate the plunger within the furnace resulted in premature failure simply due to the corrosive nature of high temperature alloys. Attempts were made to use refractory liners but then the costs became prohibitive. The only solution lay in manually ladling the molten alloy from the furnace to a 'shot chamber' attached to the rear of the fixed platen. Figure 4.3 shows a schematic of this chamber.

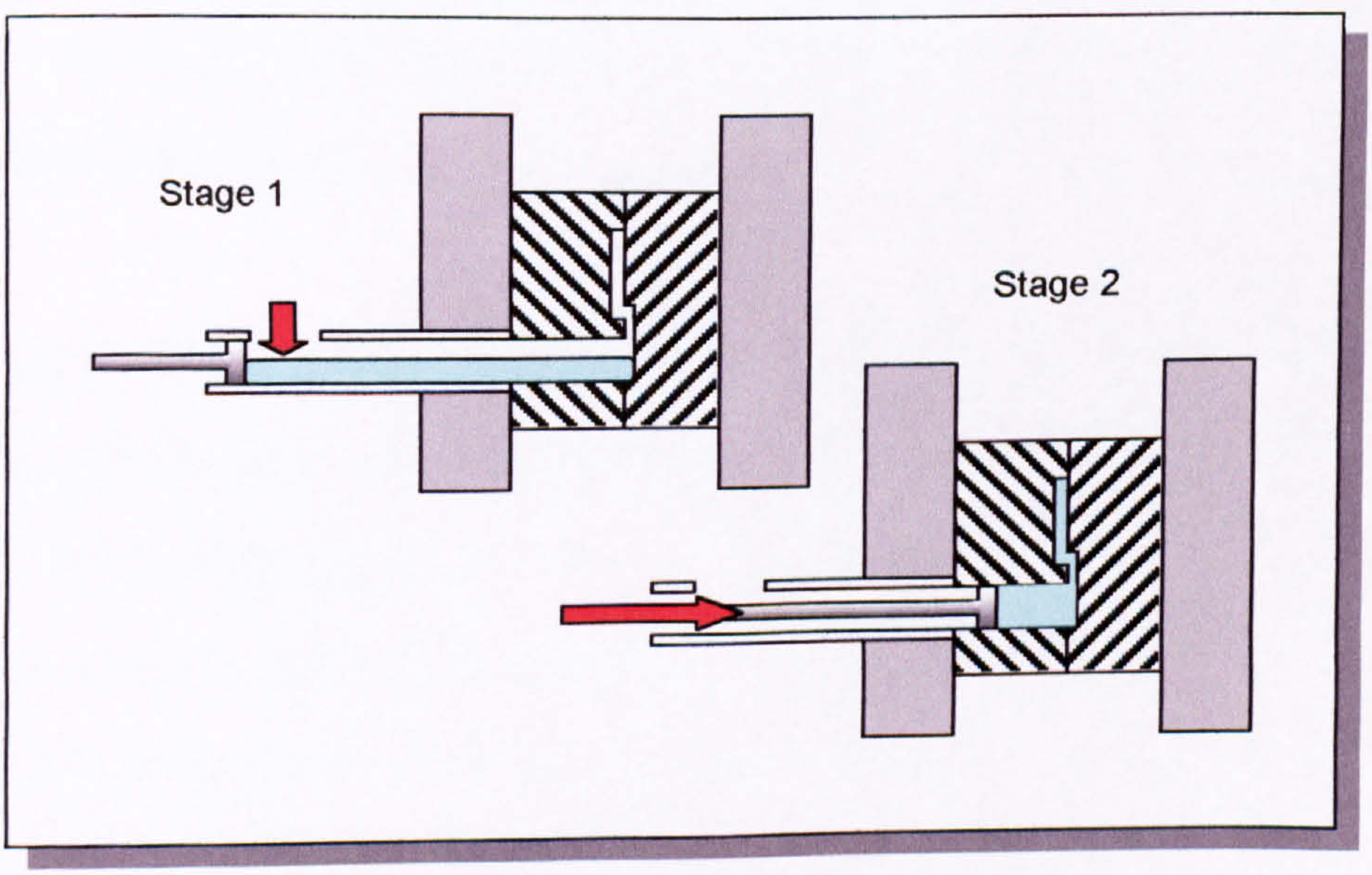


Figure 4.3 Delivery system for cold chamber HPDC

The same plunger principle is employed as in the hot chamber process with the alloy being poured into the inlet port on top of the shot sleeve. The shot is then initiated and the plunger goes through the same three phases as before. An important feature which differentiates the two processes is that when the die cavity is being constructed for the cold chamber process it must be positioned above the level of the shot sleeve. If it were below this level, the alloy would flow along the shot sleeve and into the die chamber before the shot has been initiated.

By ladling the alloy into the shot chamber just before the casting cycle, the temperature of the working components of the shot sleeve and plunger can be kept significantly lower. This is aided by additional water cooling lines which run through the inside of the plunger, so its temperature rarely gets above 300-400^{0}C before the shot is initiated. This slight modification to the process made the die-casting of aluminium and magnesium alloys possible, but there was a trade-off. In the hot chamber process, the furnace is an integral part of the die-casting machine, to reduce the distance between furnace and die, and the furnace could be completely sealed to the external atmosphere and flushed with inert gas.

The cold chamber process eliminated the use of an integral furnace attached to the die-casting machine which resulted in the alloy being ladled from the furnace to the shot sleeve. The immediate problem is that the ladle is chilling all the time it is out of the furnace, as well as oxidising the alloy within. There is also the problem that it is much harder for the operator to control the exact amount of alloy in the ladle for each shot. Certainly the operator can build up skills to compensate for this but this only goes to place the process in the realms of the 'black art' category.

4.4 Low Pressure Die-casting (LPDC)

The development of the low pressure die-casting (LPDC) process can be best understood by studying the short comings of the HPDC process.

Philbin (1996) quotes a die-casting executive as once describing the early efforts of die-casting as *"two dense skins separated by a sponge"*. This statement may be somewhat exaggerated but some of the worst examples do seem to support this statement.

Porosity occurs in the cold chamber process due to the arrangement of the shot sleeve. In the cold chamber process, the shot sleeve is only partly filled with alloy up to around 60% of its capacity. To fill the sleeve completely would result in material being ejected through the filling port during 1st phase 'take up'. As 2nd phase 'injection' is initiated, the plunger is driven forward against the molten alloy and a wave motion is set up on the surface of the alloy. As these waves break and form in the sleeve, air becomes entrained in the molten alloy.

Porosity is increased still further as the alloy enters the die chamber through the inlet gate. At this point, the material is travelling at its greatest velocity and, at some point, the flow will strike the internal features of the die. This sets up vortices and turbulence within the alloy which breaks up the flow further, resulting in an increase in entrained gasses in the casting.

Even if large quantities of gas are entrained in the casting it rarely shows up on the surface of the casting. This is due to the alloy chilling rapidly on the die surface which is significantly cooler than the molten alloy. This deposits a solid layer of alloy on the die surface with the gas pores just below the surface (it should be noted that 3rd phase compression reduces the size of these gas bubbles).

Porosity has a number of detrimental effects on a casting. As with most casting and machining processes, it is favourable to form the primary shape of the part and then go through some form of heat treatment process. This may be for hardening, normalising, or surface modification (such as anodising in aluminium). Whatever the reason, pressure die-castings can rarely be heat treated as the bubbles of gas trapped below the surface of the casting rise to the surface and result in the appearance of a blister. Porosity also affects any post-casting operations. It is futile to machine off sections of a die-casting only to expose a porous substrate.

Porosity, during the casting process, also produces localised oxidation around the gas pocket. Oxide inclusions are very hard and rapidly wear down cutting tools where machining is required, even breaking them where high spindle speeds are employed. The final consideration for these applications is when the casting is to be used for high stress applications. Gas pockets distributed randomly through a casting form unpredictable areas of weakness.

In the early days of HPDC, die-castings were generally used for more aesthetic purposes. Castings today are expected to resist all forms of stresses in their applications and this became particularly relevant when engineers began to use pressure die-castings for applications, such as alloy wheels and engine blocks. There were some spectacular failures in attempts to produce alloy wheels. Wheels collapsed on travelling vehicles and this was primarily due to crack propagation where porosity and oxide inclusions occurred.

A method was required which gave the benefits of HPDC with the elimination of its problems with porosity. The problem was addressed on two fronts. The first, was to reduce the speed of injection and so reduce the amount of turbulence which occurs in the molten alloy. The second, was to change the orientation of the entire machine to eliminate the possibility of waves forming in the shot chamber. A series of techniques now exist to overcome the problems listed above and include:

- Evacuated & Vacuum Die-casting
- Vertical Pressure Die-casting
- Counter Pressure Die Casting (CPDC)

4.4.1 Evacuated & Vacuum Die-casting

Though these two words can be used interchangeably, in LPDC there is a subtle difference between the evacuated process and the vacuum process. In both Evacuated Die-casting (EDC) and Vacuum Die-casting (VDC), the material is assisted into the die chamber by the use of a full or partial vacuum.

Eliminating atmospheric and combustion gases from the die chamber eliminates the possibility of gas pockets and oxide products forming, even if turbulence occurs within the die cavity. Clegg (1991) states that scientists who first studied the nature of porosity in HPDC castings made the surprising discovery that, when analysed, the gas present in the pores was almost all nitrogen. All the oxygen had been consumed during casting to end up as oxide inclusions within the casting.

The concept of EDC relies on an 'oxygen purge' of the die prior to the shot. This flushes any nitrogen present in the atmospheric gas out of the die vents. Oil based release agents are replaced by water based colloidal graphite suspensions in this process as they would otherwise burn intensely in the presence of oxygen. As the casting cycle begins, oxygen is introduced into the die chamber. As alloy enters the chamber it consumes the oxygen rapidly, as fine oxide inclusions, and creates a pressure drop in the die cavity which assists the alloy into the casting. This means that injection pressures can be dropped to reduce turbulence in the melt. With both processes, there is an additional cost of vacuum and purge equipment to take into account and, in both, the material is still ladled from furnace to shot sleeve and much of the turbulence which is set up is still in the shot sleeve.

4.4.2 Vertical Pressure Die-casting (VPDC)

Of the two approaches developed to overcome porosity, the second involved changing the orientation of the die and delivery system so that they sit one above the other in vertical alignment. VPDC represents one of the most successful alternatives to HPDC and relies on controlling the flow of the molten alloy from the shot sleeve to the die cavity.

By positioning the injection plunger directly below the die cavity and forcing the flow of alloy upwards into the die, many of the turbulence issues associated with wave formation in the horizontal shot sleeve are overcome. Various modifications have been made to this process, one such concept is show in Figure 4.4. Molten alloy is loaded into the vertical shot sleeve through the pouring slot where it rests on the lower plungers. The upper plunger is lowered until it applies pressure to the top surface of the molten alloy. Both plungers then descend the shot sleeve, moving the alloy into the area of the runners which fan out into the die-cavity. The lower plunger ceases its descent and the upper plunger continues down the sleeve to force the alloy out.

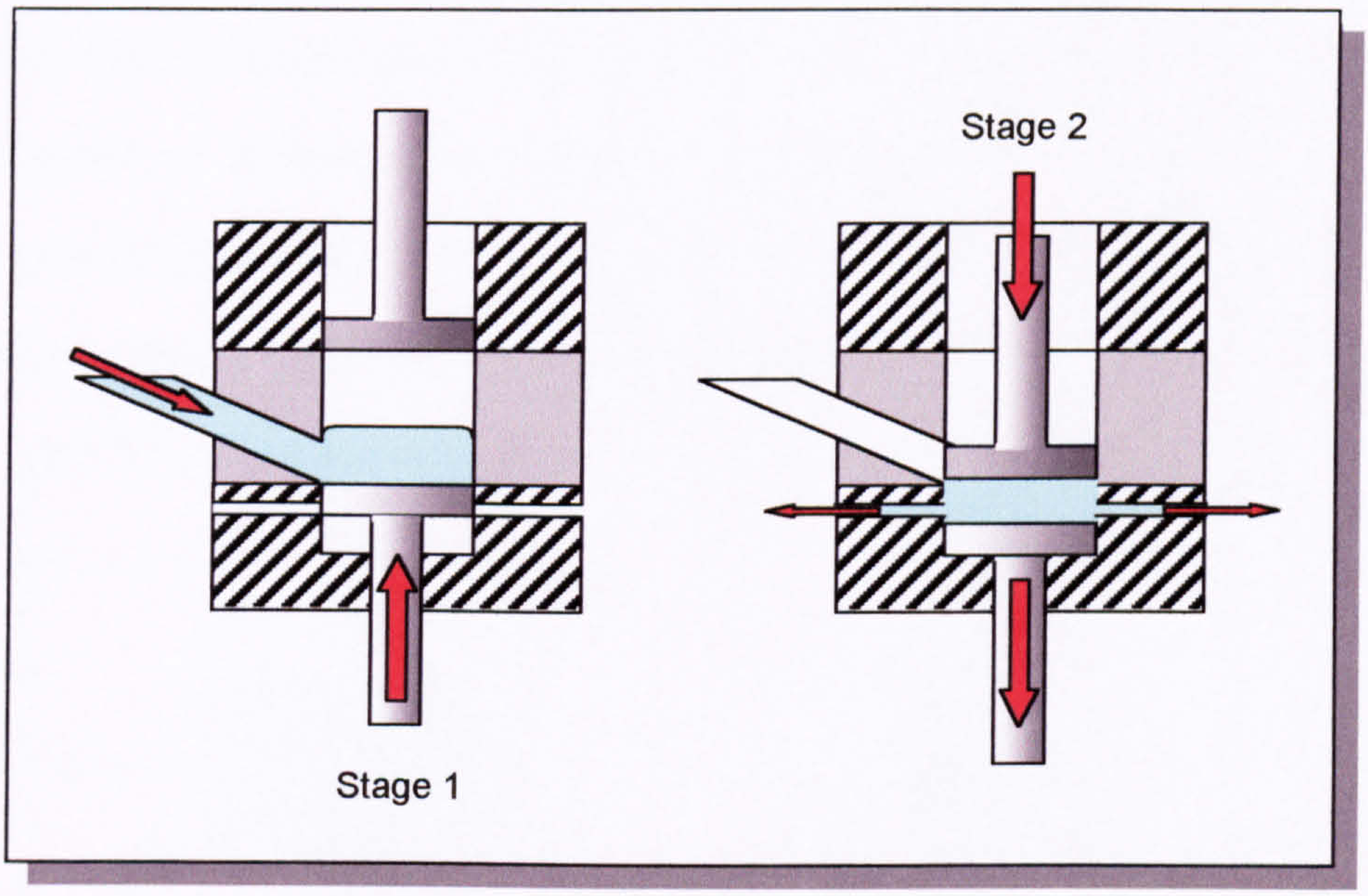


Figure 4.4 Schematic of the vertical die-casting delivery system

In this technique there is no turbulence, as the alloy is constrained between the two pistons. VPDC is the most popular of the alternative approaches to HPDC. Many of the new HPDC machines are now capable of rotating the die and injector assembly to take advantage of vertical alignment. The lower pressures ensure less wear on the die-casting elements, including the die, but this does reduce the cycle time considerably. This is the trade-off between speed of injection and quality of casting which was discussed previously.

4.4.3 Counter Pressure Die-casting (CPDC)

Developed in Bulgaria, Street (1986) notes the appearance of this machine in 1983. In the CPDC process, the focus for modification is on both the injection system and the die. Figure 4.5 shows the principle behind the process.

CPDC resembles the hot chamber process in that the furnace is directly attached to the die. Traditionally, this would have limited its use to zinc alloys but developments in refractories and ceramics and the complete elimination of the injection plunger means it can be used for any alloy. The unit consists of two hermetically sealed chambers, one containing the die and, directly below it, the other chamber containing the furnace.

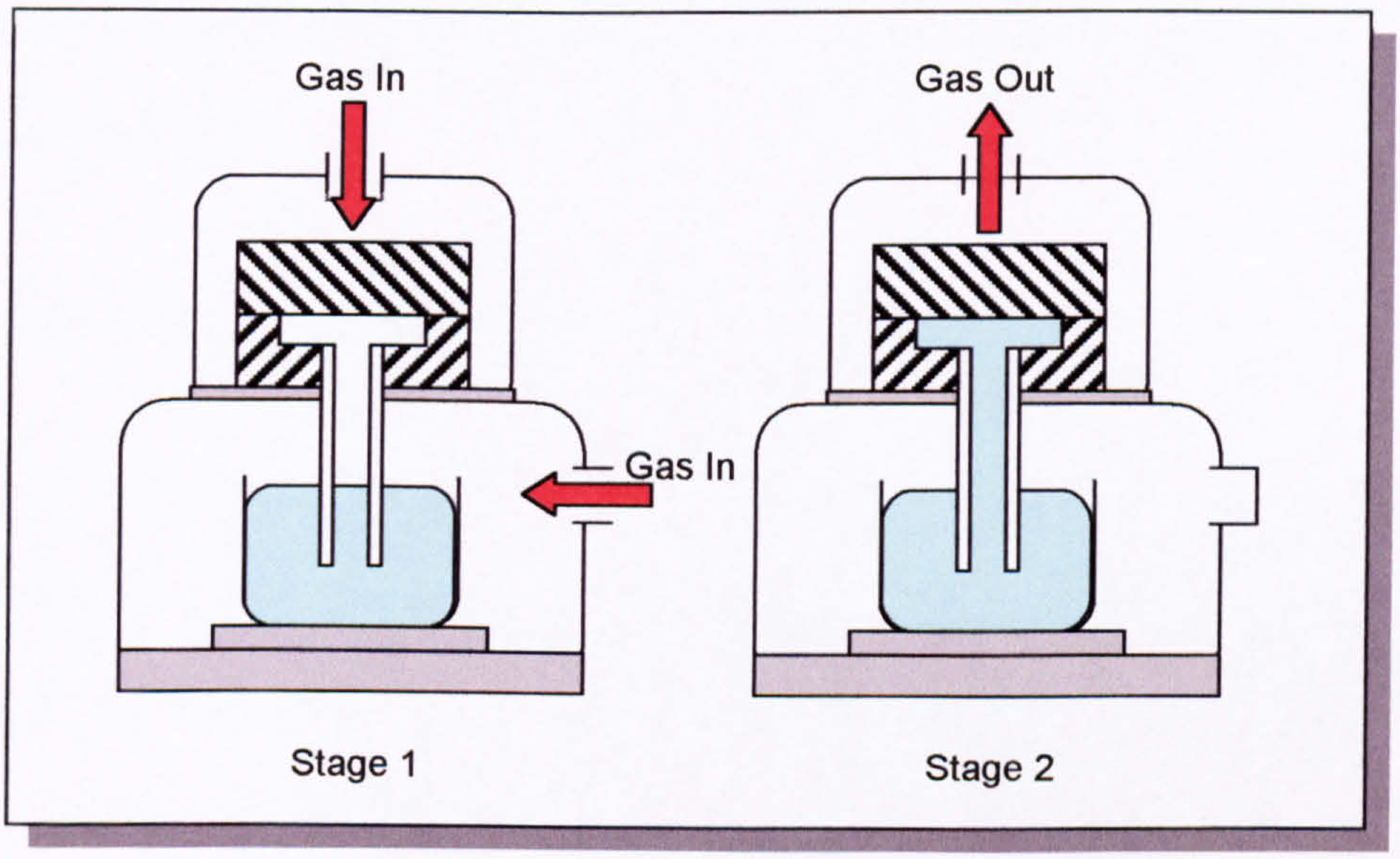


Figure 4.5 Schematic of Counter Pressure Die-casting process

With the molten alloy in the lower furnace, both upper and lower furnaces are pressurised with inert gas to around 200N/mm^2. At the commencement of the cycle, the pressure in the upper furnace is bled out creating a huge pressure differential which drives the alloy up the delivery sleeve and in to the die chamber. The rate of pressure release from the upper chamber is controlled so that all turbulence is eliminated.

With the die completely filled with alloy, the pressure in the lower chamber is maintained and this continues to feed alloy to the casting as it shrinks. This results in a completely homogenous casting with no inclusions through oxidation and no porosity. The casting exhibits virtually no shrinkage from the surface of the die as it cools, and can then go on to be machined and even welded (always considered impossible for HPDC parts where porosity occurs).

The process is ideal for large precision alloy castings, such as alloy wheels and engine blocks, where the quality of the casting overrides the importance of the time between shots. It does, however, require investment in new equipment over the vertical pressure die-casting process.

4.4.4 Squeeze Forming and Semi-Solid Metals (SSM)

Pressure die-casting, in whatever form, is always working on the extremes of what is technically possible at the time. New processes are continually under development, each attempting to overcome one or other affects that make the process difficult to control. The latest endeavours attempt to overcome the problem of die fatigue.

The constant and rapid thermal cycling that a die must endure place it under considerable stress. New die steels are continually introduced to overcome these problems but all degrade at some point due to the harsh operating conditions. Zhukov *et al* (1994) observe that most of the problems with thermal fatigue or 'heat checking' occur in the few fractions of a millimetre from the surface of the die. This thin layer receives the full heat of the molten alloy before it is quickly conducted away through the die. This may be for only a fraction of a second but, in this surface layer, the temperature is well above the annealing temperature for tool steel and it is here that a migration (diffusion mobility) of carbon atoms can begin, resulting in intercrystalline failure along the grain boundaries. Zhukov also observes that even though the reason for the propagation of cracks differs greatly for different types of tool steel, it will still occur to a greater or lesser degree.

Squeeze Casting, and the Semi Solid Metals it uses, utilises this intercrystalline failure in the alloy and not the die. The concept being to reduce the thermal cycling on the die by reducing the temperature that the casting alloy is delivered to the die at, during casting, without losing the benefits to be gained from aluminium and magnesium alloys.

Work began on this process in the 1970's and has been attributed to various groups, including MIT and the Fulmer Research Institute, who all contributed to its development. The key to the process lies in the modification of the grain structure of the alloy as it reaches the point between 'liquidus' and 'solidus'. The alloy is first heated to its liquidus state and then allowed to cool slowly to the point when crystalline growth begins. The alloy is then vigorously agitated to produce slurry in which the dendrites are broken down into globular solid particles. This is then classified as a Semi-Solid Metal (SSM).

Clegg (1986) states that even with a 50-60% 'solid' content, if the alloy is continually stirred, it retains a low viscosity. If agitation is stopped, the material, though still 50% liquid, could be handled as a solid 'putty'. The key to casting such material is in its thixotropic structure. As soon as pressure is applied to the alloy, it shears along the grain boundaries and flows as a fully molten material. Thixotropic alloys or Semi Solid Metals (SSM) can be cast at 100^0C degrees less than their normal melting temperature.

The Rheocasting process utilises SSM alloys with the conventional HPDC and LPDC processes. The SSM alloys are produced through agitation but are allowed to cool completely to room temperature where they still retain this structure. They are then cut up into set slug sizes and loaded into the die casting machine for each shot.

The shot chamber contains it own heater to raise the temperature of the SSM slugs to injection temperature, thereby eliminating contamination from the atmosphere as well as delivering very accurate volumes of alloy into the die cavity. The casting cycle is slower at around three seconds but as a viscous material it will not splash around the die during casting.

In a similar vein, GKN developed the Squeeze-forming process. This resembles a forging technique. The heated thixotropic material is loaded into a pre-heated, two-part, die which is then forced shut and sealed. As it closes onto the alloy, the force heats the alloy further causing it to flow around the die. This process eliminates the need for any injection equipment and is very fast. Philbin (1996) states that there are no porosity and gas related defects and the castings can be heat treated and welded with very high integrity.

Reducing the overall temperature which the alloy needs to be to cast, opens up an entirely new field of opportunities. With lower injection temperatures, both steel and copper SSM alloys may one day be cast, to some degree, in conventional pressure die-casting machines.

4.5 Current Die-casting Research

In the UK the die-casting industry is fairly fractured (Birch, 1999). What few specific die-casting organisations that did exist have now largely been disbanded, or merged into larger confederations involved in casting or alloys generally. Because of this, there is no national strategy for furthering die-casting and die-casting applications. This cannot be said for the US.

The single most important interest group in this field is the North American Die-casters Association (NADCA) who have outlined its objectives for developing die-casting well into the next century. This 'strategy' implementation is not limited solely to US research groups but is being undertaken all over the world.

Research and development efforts are driven by the Technology Administration Group and three committees; the Die Materials Committee, the Research and Development Committee and the International Technical Council. NADCA is a completely integrated part of the research and funding distribution chain working directly with the various funding bodies in the US. Their 'Beyond 2000' vision statement (1999) is as much a statement on the entire field of die-casting research.

The paper itself is quite extensive but does show the breakdown of those areas highlighted by the industry as crucial for development. These areas are reproduced in Figure 4.6 .

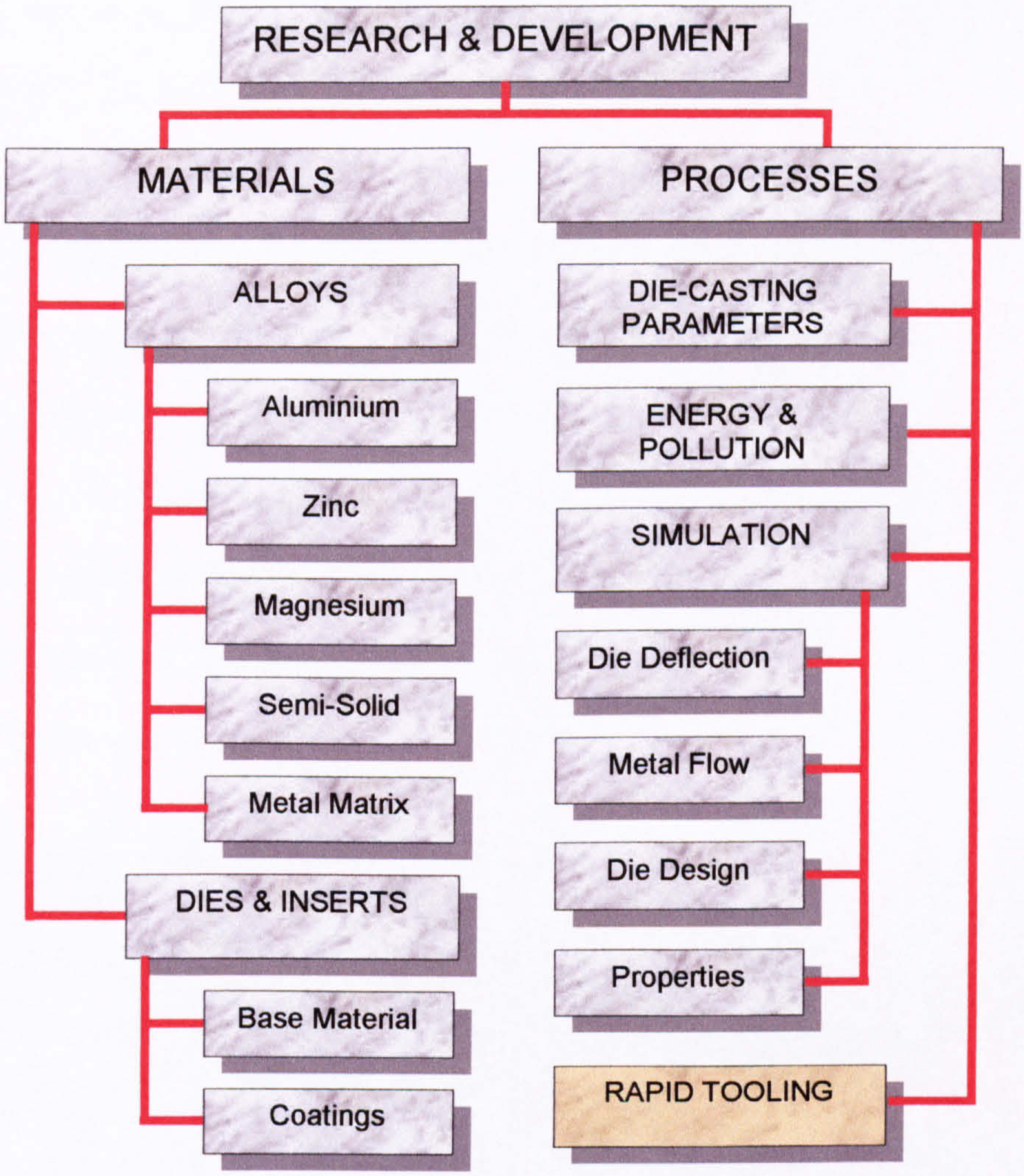


Figure 4.6 NADCA's research areas for the 'Vision 2000' strategy

The different areas identified in this report and the work being done to realise them are now summarised.

4.5.1 Materials

The ability of the materials used in die-casting, to withstand the environments in which they are used, is critical to the process's success. This applies to both the alloys used in the casting process and the base materials used to form the dies. Material properties also extend well beyond the casting process itself, as most die-cast parts will be required to operate in the harsh environments found in automotive, aerospace and construction applications.

As much as ensuring that the alloys are free from impurities during the casting process, it is equally important to ensure that they are free from impurities during their refining. Until now, die-casting alloys have been expected to have the equivalent mechanical properties to medium strength metals (low carbon steel, brass etc) but this is changing with new die-cast alloys such as the ZA range which offer excellent bearing properties. Figure 4.7 shows a main bearing casting for an All-Terrain vehicle produced by the Die-casting Development Council (1999[2]) and Twin City Die-castings Inc.

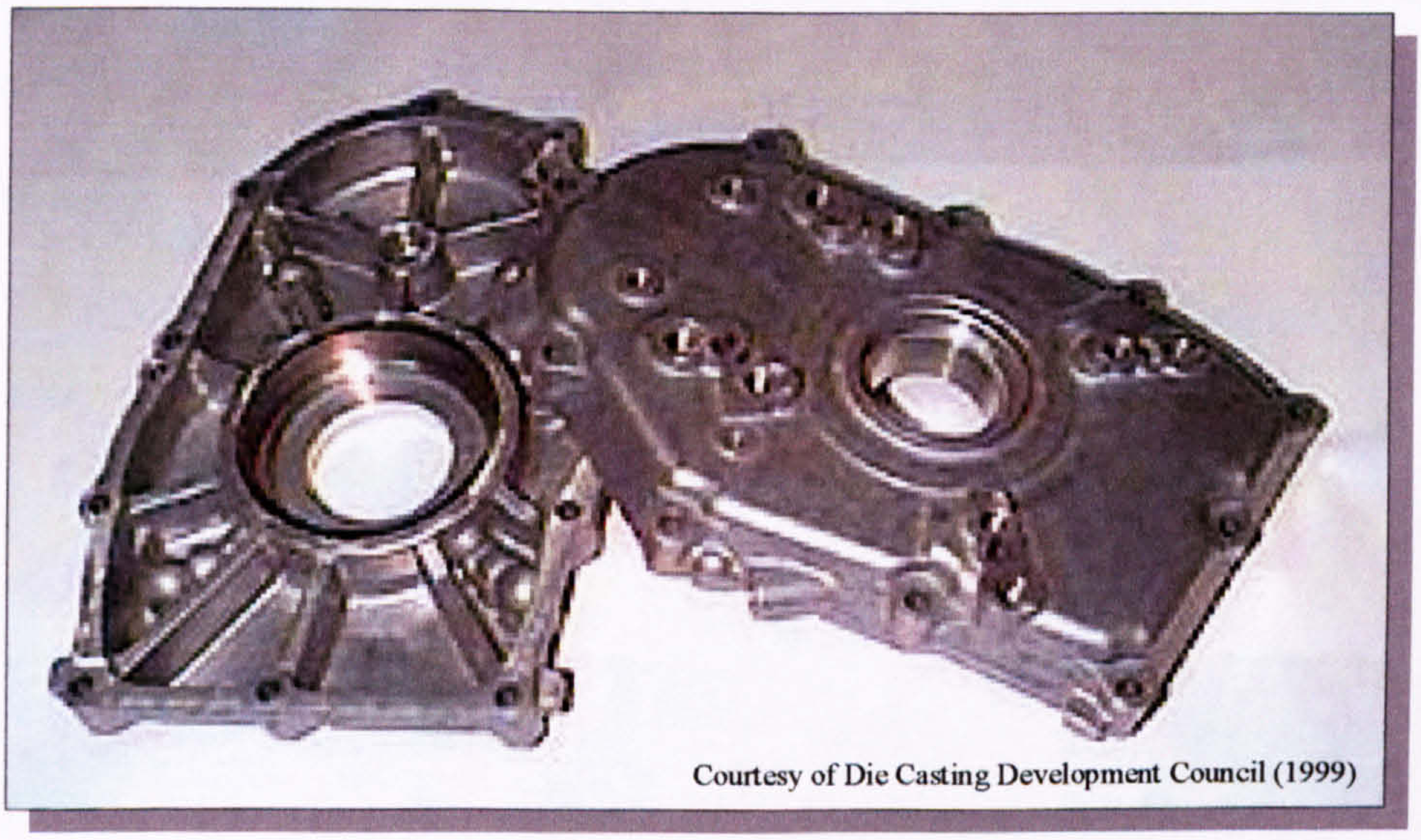


Figure 4.7 Structural die-cast alloys for load bearing applications

This structural component was possible with new die-casting alloys which made HPDC the cheapest option for production of the part, over the traditional permanent mould and sand-casting techniques. The tighter tolerances in die-casting offering a $20 saving in machining costs per part over the other processes considered.

Material development at the University of Alabama, USA (NADCA, 1999[3]) has also opened up many new fields to the die-caster over conventional machining and casting. Die-cast alloys with material strengths up to 415MPa (ultimate tensile) allow the designer to produce thinner walled sections. Die-casting also allows the flexibility to include flanges, ribs and locally thickened sections within one casting operation and no secondary finishing.

Along with the development of better die-casting alloys, the University of Tennessee (NADCA, 1999[3&4]) is opening the new field of Semi-Solid Metals (SSM) and Metal Matrix Composites (MMC) that were discussed previously. These materials are opening the possibility of casting materials such as copper alloys, stainless steels and steel SSM alloys without the detrimental effects to the die that would be expected in unmodified materials.

The dies themselves, and the tool steels used to produce them, are under constant development. Due to the difficult nature of the die-casting process die-casters like to stick to what they know. The use of H13 tool steel will be discussed in the next chapter but there are a host of alternative die steels under development. The use of the Hot Isostatic Press (HIP) to forge billets of die steel from very finely ground steel alloy powders gives a far more refined and homogenous grain structure to the die. Processes such as the marraging of steel have been around for some time but need to be brought to the attention of the die makers.

4.5.2 Die Coatings

A new area of interest is the development of die coatings. One of the key advantages of the die-casting over other casting processes is the ability to use 0^0 draft angles with no shrinkage from the die surface during solidification (NADCA, 1999[3]). Achieving this, in reality, is not simple and the cost of die construction normally results in the designer erring on the safe side by incorporating some draft angle. The key to consistent ejection of the casting from the die is in the release agent used. It has already been noted that aluminium alloy has a tendency to solder to die steel under certain conditions. The release agent used is critical in preventing this. However, there are not many materials that can withstand the attack of molten alloy being forced against them.

In the past, this problem was addressed from various angles. Oils were commonly used with the intention that as alloy came into contact with the oil it would burn fiercely and leave a deposit of carbon on the surface of the die. Burning oil presented its own problems, in that it was strongly suspected as the cause for much porosity in early pressure die-casting systems.

An alternative was found with the suspension of colloidal graphite powder in a water base. The graphite, acting as an inert release agent, and the water being only required to deliver an even coating of graphite to the die face. Even so, both these systems resulted in a very poor surface finish to the casting due to the residue left.

Today's die-casters use a variety of agents, the most popular being based on emulsified silicon (polysiloxane) in a water medium. These agents result in a very clean and bright casting. Systems now exist which will deposit a tenacious Teflon coating which require replacement on a weekly basis.

All these processes have increased the cost of the release agent and, considering that a litre of agent may be applied to the surface of a die on large castings between shots, there is a lot of interest in reducing wastage. The solution is to apply the success the paint industry has had in reducing its consumption of paint.

Two die-casting companies (to the author's knowledge), Frech AG in Germany and Bühler AG in Austria are now testing a process whereby the atomised release agent is electrically charged, on release, through the spray nozzle. By applying an opposite charge to the die surface, it is possible to direct that spray only to the die surface which is charged. By varying the charge over the die face, it is possible to control the amount of agent deposited at any one point on that surface.

4.5.3 Die-casting Parameters

The search for the optimum operating conditions for any one product is never ending. All castings have their own operating requirements which require subtleties in the design of the die and the parameters for casting. NADCA, as with all die-casting associations, direct much of their efforts refining the process parameters for new machines, new materials and new products for the benefit and dissemination to their members.

As an example, Prince Machine Corporation (1999) have developed Pro-filer Shot Control for those companies unable to completely re-invest in the new SSM technologies which are emerging. Analysis has shown that by controlling the plunger speed, upon injection, it is possible to set up a wave in the molten alloy which will effectively purge the shot sleeve of gasses. With a few modifications, the effective plunger speed, during the 2nd phase 'injection', can be increased or decreased to prevent this wave or surge from breaking up in the shot sleeve which would normally result in the entrapment of gas within the molten alloy.

The Die-casting Development Council (1999[1]) have recently published standards relating to tolerances for speeds, die life, maintenance and precision. Precision guidelines relate to shape, features and wall thickness transition. On a more global level, they are implementing the acceptance of Geometric Dimensioning and Tolerance (GD&T) as a means of standardising the symbols and geometric tolerance techniques the designer should apply to part specifications. By defining potential defects and the conditions in which they occur, they also hope to set quality standards through statistical quality control, process variables and procedures for first-piece inspection.

In a related project, the University of Alabama at Birmingham, USA (NADCA, 1999[3]) are undertaking research based around casting reliability. By analysing the castings taken from a production foundry, they hope to construct suitable solidification modelling leading to reduction in porosity in castings. New measurement techniques form the backbone of this work, such as 'digital x-ray' and 'swept wave ultrasonics' which will allow them to study micro-porosity and its affect on mechanical properties.

4.5.4 Simulation

Simulation, as with all other areas of industry which have benefited from the computer, has come into its own in the last few years. This field has always been limited by the level of the technology available at any particular time. With the ever increasing pressure to reduce the initial die production costs it is essential that the die designer has some means to look at the affects which his or her designs will have on issues such as:

- Temperature distribution around the die
- Direction and nature of the flow around the die cavity
- Effects on the die during casting
- Effects of stress on internal features during casting.
- Effectiveness of design of thin walled sections.
- Adequate and even flow through inlet gates.

Even today, many die designers still rely on their knowledge of a system to estimate what will happen to their die during casting. This ultimately leads to over engineering of the die produced with no indication of how it will perform until it is sitting between the platens awaiting that first shot - this carries a risk!

The implementation of Finite Element Modelling (FEM) into die-casting has been hindered by the size of the calculations required to model any of the issues listed above. Modelling made its first appearance looking at temperature distribution around the die during casting.

Modelling of temperature through solids is relatively straightforward, compared to the Navier-Stokes analysis done today on molten fluids passing around a die cavity. Even so, ten years ago, such calculations could have been running for a week requiring extremely expensive hardware. Thermal analysis is now relatively established within die-casting design and FEM fits neatly into the move towards CAD modelling. Most CAD packages now offer an FEM extension for just such purposes as shown in Figure 4.8.

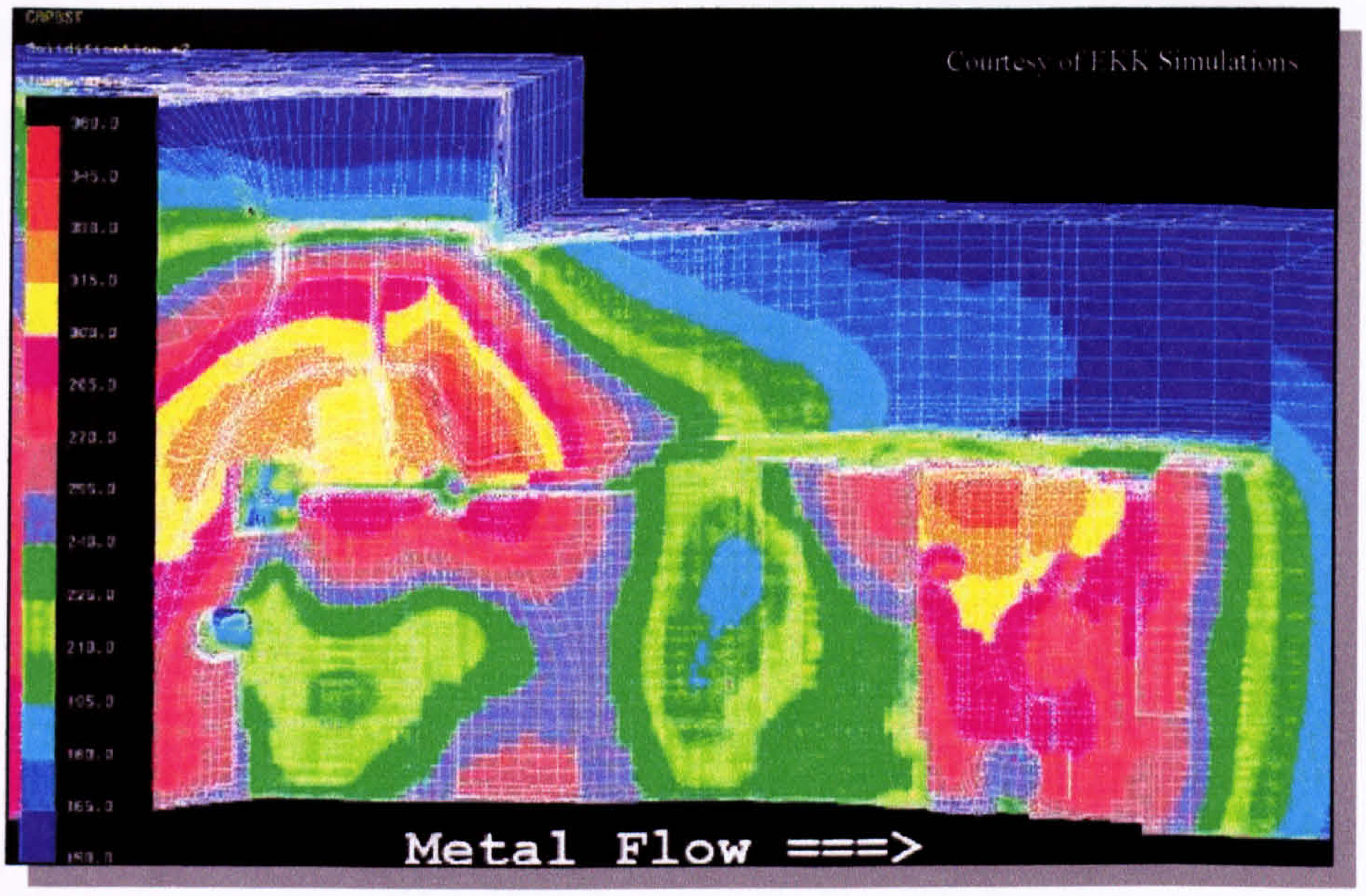


Figure 4.8 Thermal distribution through a casting

Two areas are currently under development at Ohio State University (NADCA, 1999[3]):

- Die-casting reject reduction.
- Dimensional control of die-casting dies.

The starting point for the reduction of rejects was to identify an emerging problem in the die-casting industry. This was that die-castings are often produced infrequently and in small batches of 100-1000 parts.

This is a fundamental shift away from the traditional view that a die would be run for hundreds of thousands of parts. This condition clearly reflects the changing market place with continuous product development and the growing field of niche markets. All these influences shorten the time the die will be required at any one time.

The problem they identified is that under normal conditions where many tens of thousands of parts are produced in a day there is no real problem in 'running the machine in'. This is where the first ten or more castings will be rejected, as the die-casting machine has not warmed evenly. If the machine is not at its optimum operating condition then this can lead to problems with liquid metal flow and casting solidification.

Ohio State University hope to understand 'running in' better through the use of high speed infrared die temperature measurement and the use of flow simulation of molten alloy as it fills the die cavity as demonstrated in Figure 4.9.

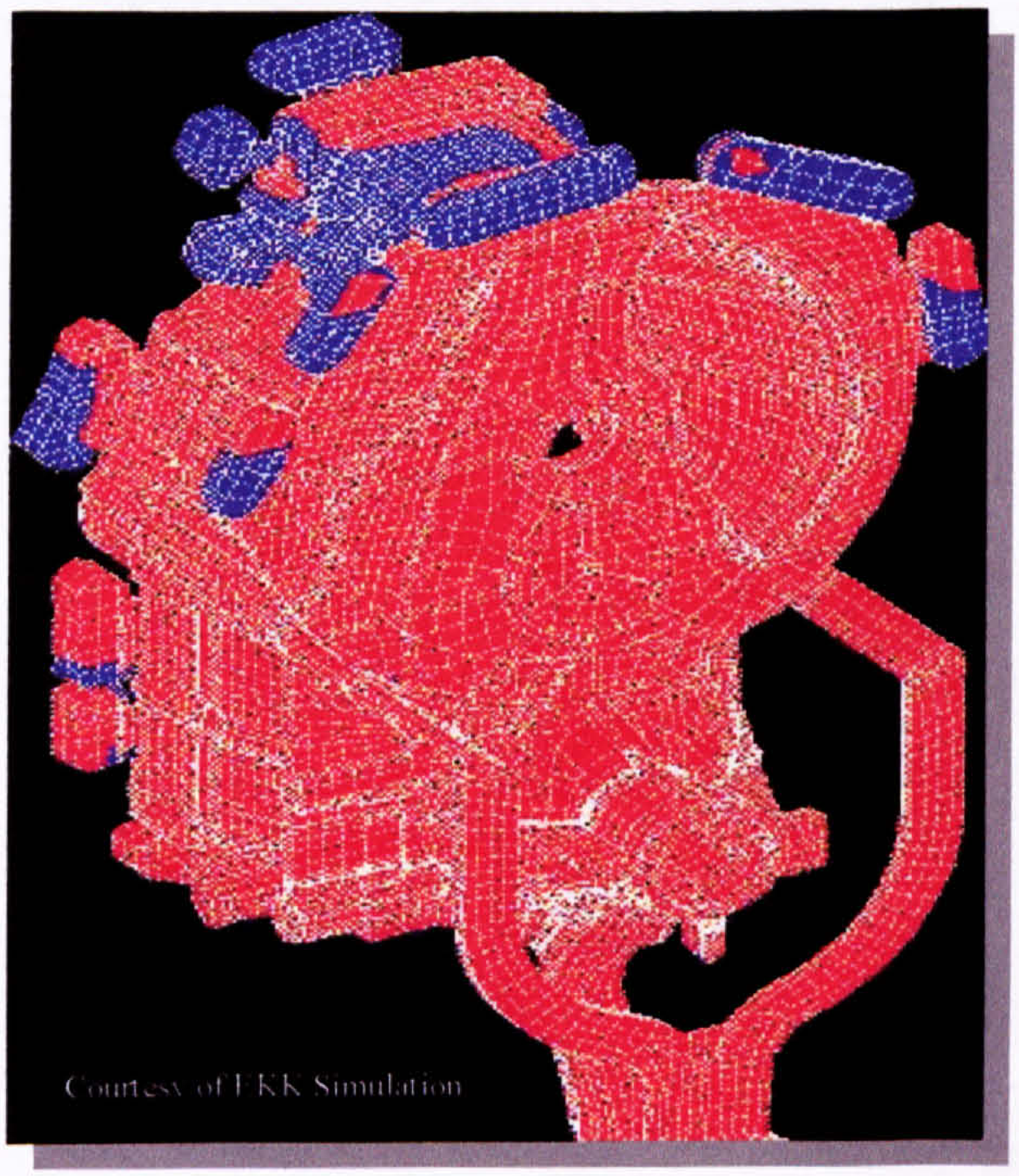


Figure 4.9 Solidification and flow simulation software

The second area, and one which is most commonly overlooked, is to study the behaviour of the die during the casting cycle. Miller *et al* (1996) observe that elastic deflection of the die, during casting, can seriously affect dimensional and process tolerances and, at worst, prevent the die from functioning at all.

Through FEM analysis, they have been able to show movement of almost 0.3mm between the two halves of the test dies where 69MPa clamping pressures are applied along the parting line. Their aim is to develop the model of deflection further so that it can be built into the operating software on new machines and be linked to some form of 'in-situ magneto-elastic' measurement to give a closed loop feedback during the casting cycle.

4.5.5 Rapid Tooling for Pressure Die-casting

The final area that NADCA identify, in their Vision 2000 statement, as crucial to the future advancement of pressure die-casting is the implementation of Rapid Prototyping and, subsequently, Rapid Tooling techniques into the heart of the industry. A review of the work done so far by research groups around the world follows in Chapter Five.

Chapter 5: Rapid Prototyping and Rapid Tooling for High Pressure Die-casting Applications

5.2 Introduction

NADCA (1999[3]) state that Rapid Prototyping and Tooling (RP&T) techniques could offer the greatest immediate savings to the pressure die-cast industry. Traditionally, pressure die-casting offers the cheapest form of manufacture but this comes with the greatest risks.

Warner and Renaud (1995) observe that even though the argument for prototyping in the pressure die-casting sector is the greatest, most pressure die-casters rarely consider prototyping as a means of reducing errors in the die design. This does not indicate an aversion to prototyping on their part, but simply that the prototyping methods which do exist rarely give a true indication of how the production tool will actually run or what the condition of the castings from that tool will be. This is an important point as, up until the commencement of this research, there existed no method by which a prototype tool could be produced, cheaply and quickly, which would allow the die-casting designer to appraise the effectiveness of a die design before the tool was made.

The traditional prototyping techniques that do exist normally attempt to mimic the casting which will ultimately be produced from a die design. Prototype castings are useful for fit, form and function appraisal and the outcomes do directly affect the die design but they give no indication of how the die will perform once in full production. A myriad of decisions must be made by the designer to ensure that, not only will the die work, but that the process is working at its optimum. Even so, the ability to appraise a design through the production of prototypes still adds value to the design process and this can be greatly enhanced through the application of Rapid Prototyping techniques.

Some Rapid Prototyping techniques have already been attempted and will be discussed later in this chapter. The major gains to the industry, however, will be the implementation of Rapid Tooling techniques which would allow the designer to generate multiple iterations of a die design before the actual production tool is made. These too will be considered later in this chapter. What follows is a description of the conventional prototyping techniques so that the RP&T issues, discussed later, are in context.

5.2 *Traditional Prototyping Techniques*

There currently exist four approaches for the production of prototype pressure die-cast parts:

- Machining.
- Sand casting
- Investment casting
- Plaster mould casting

5.2.1 Machining

Machining a prototype part from solid stock is probably the most popular method used to generate prototypes in the pressure die-casting industry. The concept requires the use of a similar alloy (zinc, aluminium or magnesium) to that used in the pressure die-casting process. It is fast and inexpensive, where the design is relatively simple, and has been enhanced through the development of multiple axes CNC Machining.

5.2.2 Sand Casting

Sand casting is probably the fastest technique used to produce a prototype casting. A pattern must be produced, with draft angles, to allow it to be removed from the sand mould formed around it. The prototype casting will normally require some form of secondary finishing to remove runners, risers etc and modification of the surface of the casting to match the finish on a pressure die-cast part. The process is very scaleable and is probably the cheapest approach to an aesthetic reproduction of the pressure die-cast part.

5.2.3 Investment Casting

Investment casting can be used to approximate the surface finish of the pressure die-cast part effectively. The process begins with the production of a 'master' from which moulds are produced in which wax is formed to produce multiple 'patterns'. The use of multiple patterns significantly reduces the cost of this process over the other four and offers the added advantage that no draft angles are required on the wax pattern as it is melted out of the fired ceramic shell. Investment casting can also reproduce fine features and thin sections in the casting which are not possible in the sand casting process.

5.2.4 Plaster Mould Casting

Plaster mould casting is the most expensive option of the four, traditional, prototyping processes due to the tooling required. It is the process which can best reproduce the fine surface finish and detail found in pressure die-castings. Draft angles can be eliminated by the use of intermediate rubber tooling into which the plaster moulds are cast.

The geometry of the master or pattern (dependant on which approach is used) may need to be altered from that of the pressure die-cast design to take into account any undercuts which would normally be achieved through the use of sliding cores in the die-casting process. In addition, the plaster moulds are robust enough to allow partial evacuation to enhance thin walled sections. Secondary finishing is again required to remove runners, risers etc.

These four processes do, however, have serious limitations which go towards the pressure die-casters aversion to using them. Warner and Renaud (1995) identify the following drawbacks:

- Grain Size and Structure
- Mechanical Properties
- Surface Finish
- Corrosion Resistance
- Linear Tolerance
- Draft Angles
- Porosity

5.2.5 Grain Size and Structure

When machining a prototype part from solid stock, the grain structure of that part will have the structure of the billet it came from. Pressure die-casting imparts its own unique grain structure due to the flow of the alloy through the internal sections of the die and, most importantly, the 3rd phase 'compaction' refines this structure further.

With all the casting processes, there is a significant difference between each when comparing the heat transfer from the alloy to the mould. Sand, clay and plaster moulds all have much lower thermal conduction than die steel. The faster the cooling rate of the molten alloy, the finer the grain structure and, consequently, the higher the strength of a pressure die-cast part over a sand or plaster mould part. Warner and Renault (1995) studied this in detail and the effects are shown in Figure5.1.

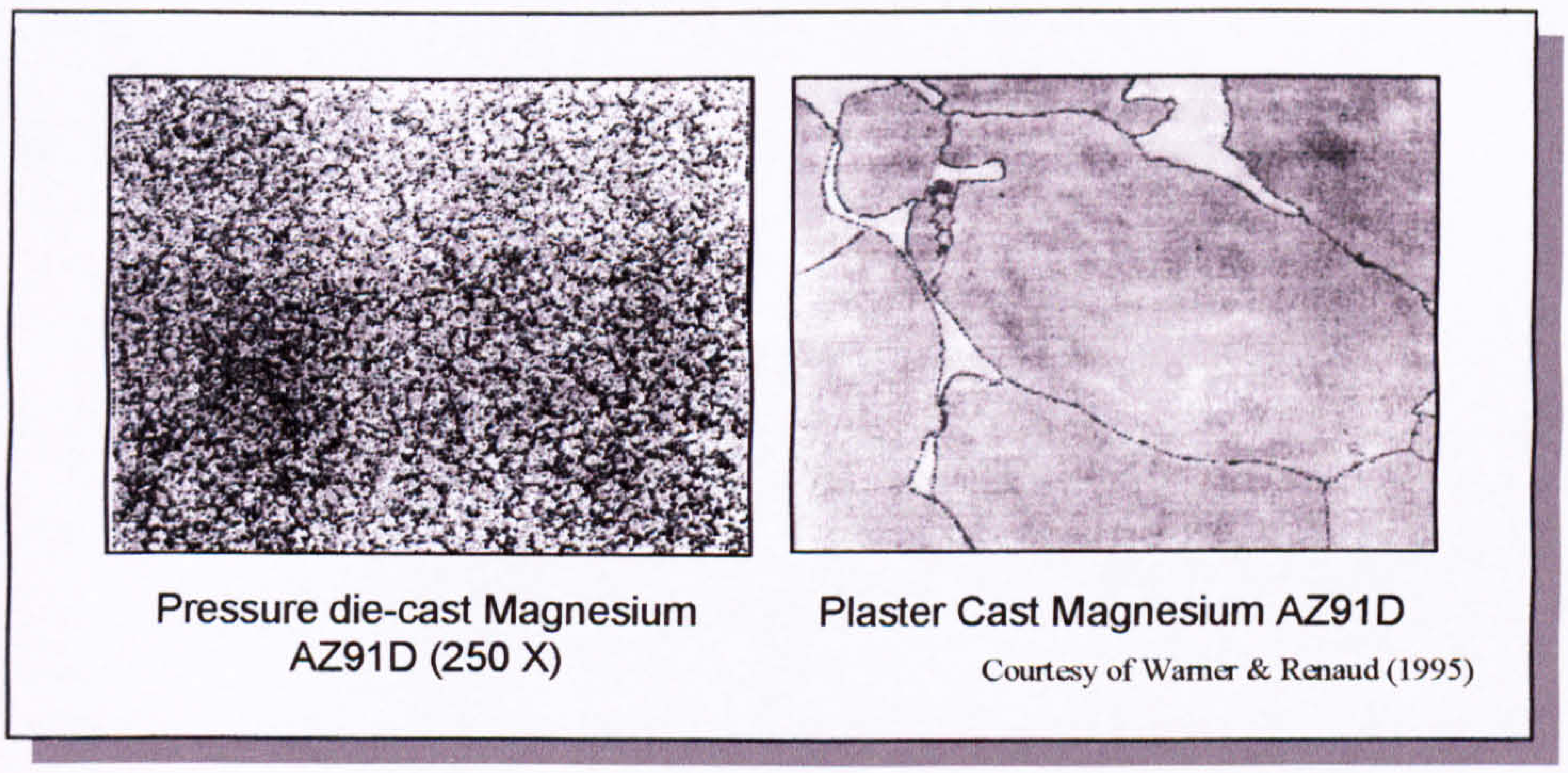


Figure 5.1 Structure of moulded part and pressure die-cast part

5.2.6 Mechanical Properties

Ideally, the type of alloy used in each prototyping process must match the mechanical properties of the pressure die-casting alloy which will be used. This presents certain problems, especially when alloying elements are present for reasons of fluidity and not machinability. Wrought materials used for prototypes exhibit high ductility and very low compressive yield strength compared to pressure die-castings. Castings taken from the sand and plaster moulding processes are often heat treated to bring properties, such as ductility and yield, closer to pressure die-cast parts.

Many pressure die-cast alloys are inappropriate for the prototype moulding techniques. Zinc alloys, designed for pressure die-casting, commonly contain up to 4% aluminium which makes them sensitive to the reduced solidification rates present in sand and plaster prototype moulding and this, ultimately, adversely affects their mechanical properties.

Many of these differences have been addressed and there exist a range of alternative designated moulding alloys with properties close to their pressure die-casting counterparts. A comparison of the mechanical properties of the different prototype moulding processes of magnesium alloy AZ91D compared to pressure die-casting, was conducted by Warner and Renaud (1995) and is reproduced in Table 5.1.

	U.T.S. (MPa)	Y.S. (MPa)	E (%)
Sand castings (min. value)	235	110	3
Sand casting (typical value)	270	130	5
Plaster casting (grain refined)	170	108	2.5
Plaster casting (grain refined & chilled)	250	120	5
Pressure die-castings ASTM B94-80	**230**	**160**	**3**

Table 5.1 Comparison of mechanical properties of Mg alloy

5.2.7 Surface Finish

Commonly called 'skin effect', the term relates the unique way in which alloy in the pressure die-casting process forms a dense skin (approximately 0.5mm deep) at the surface of the die. This process is unique to pressure die-casting, and is fortunate, in that any entrained pockets of gas are rarely visible on the surface of a casting (as they are on sand moulding processes). This 'skin' is dense and imparts its own unique mechanical properties to the castings, similar to case hardening in steel components. Where surface finish is a prerequisite then only plaster mould casting can offer similar results.

5.2.8 Corrosion Resistance

The final application of a casting will often dictate the type of casting alloy used in the casting process. For automotive components, these applications may be corrosive. Corrosion resistance is not only influenced by the microstructure of the casting but also the surface conditions which interact with the corrosive environment. Again, the 'skin effect' becomes an important factor in the comparison of pressure die-casting components as opposed to the machining or moulding processes. Other factors which influence resistance to corrosion are the impurities in the surface of the part.

In the pressure die-casting process the castings are relatively clean, save for traces of release agent, due to the fine finish and strength of the die. In the prototype moulding processes, there are always traces of the mould material (sand, clay, silica etc) entrained in the surface of the prototype part. These traces of mould material may form areas of weakness in the casting.

5.2.9 Linear Tolerance

The tolerances of a casting are only as good as the casting process employed to meet them. The coarse structure of the sand, used in the sand casting process, severely limits the amount of detail which can be reproduced and, consequently, the tolerances of the casting. Warner and Renaud (1995) calculated tolerances for sand and plaster castings as typically:

- $\pm$ 0.25mm for dimensions up to 150mm (across parting line)
- An additional 0.02mm per 25mm thereafter.
- Maximum of $\pm$ 0.5mm.
- $\pm$ 0.1mm for dimensions to 150mm (between points in mould)

The production of cores for internal details on a sand cast prototype will further affect these tolerances which are far in excess of those found in pressure die-casting. Sand castings must commonly be 'finished' to achieve the required tolerances on the casting, whereas pressure die-cast parts are produced to near-net-shape and require little, if any, finishing

5.2.10 Draft Angles

Though not relevant in the machining, investment casting, and, to some degree, the plaster moulding process, a draft angle of 1-2^0 is necessary to extract the 'pattern' or 'master' from a sand-cast mould. This, not only, adds weight to the prototype casting but also affects the prototype's mechanical properties.

5.2.11 Porosity

Porosity is an issue in all casting/moulding processes and the porosity of a pressure die-cast part has been previously discussed. Machining and sand casting produce dense parts, compared to pressure die-cast parts. Warner and Renaud (1995) have shown that, though plaster cast prototypes exhibit similar porosity to die-cast parts, they will generally have a higher density than their pressure die-cast counterpart.

5.3 *Rapid Prototyping for Pressure Die-casting*

The traditional prototyping techniques, listed above, cannot be described as rapid solutions. Apart from machining, all rely on a lengthy process to form a master or pattern (be it wooden, wax or plastic) around which a mould is formed. In 1992/3, Mueller (1995[1]) observes that various groups began to explore how Rapid Prototyping techniques could enhance the pattern making processes and, therefore, make them more attractive to the pressure die-cast designer. Their objective was to reduce the time taken to produce the master, or pattern, from which a mould is formed.

The obvious candidates to penetrate this field were those Rapid Prototyping processes which had been modified to form the 'indirect' Rapid Tooling methods discussed in Chapter Two. These were Laminated Object Modelling (LOM), Stereolithography (SLA), Selective Laser Sintering (SLS) etc. which could produce a master, or pattern, for one of the traditional prototype moulding processes listed above.

The first such system was demonstrated by American Precision Castings Inc. (Kowalczyk, 1994) in which LOM paper models were produced as a master. They wished, ultimately, to form plaster moulds for prototype castings and had to include an intermediate step to the process so that multiple patterns could be generated from the one LOM master. If the plaster slurry were to come into contact with the LOM master it would have expanded and disintegrated through the absorption of water from the slurry.

The 'intermediate' stage produced epoxy resin patterns and it was around these 'stable' epoxy patterns that the plaster moulds were formed. The tool produced ten prototype castings within eight working days from the start of the project.

Close behind, came a similar study by Warner and Renaud (1995) at the Institute of Magnesium Technology, in which more stable SLA patterns were used to form plaster cast moulds with no intermediate stage. They had previously identified the need for prototyping techniques to produce parts over 500×500×500mm but to produce SLA patterns over this size, at this time, was difficult and was overcome by bonding multiple SLA parts together to form the pattern. From that point, the construction of a plaster cast mould or a sand cast mould was the same as the traditional approach.

Even though none of the drawbacks associated with the prototype moulding processes were overcome, they were able to show a 40-80% reduction in the time taken to manufacture a prototype part.

5.4 Rapid Tooling for Pressure Die-casting

Mueller (1995[2]) states that the cost of discovering design errors after the tool is complete can be staggering. He estimated that around 75% of all dies produced require some form of rework, be it incorrect gating, wall thickness, ejection, hot spots etc. The average cost of rework is 10% of the original cost and the act of rework will diminish the life of the tool by approximately 25%. This additional work requires time, which may be as much as 3 months, and this represents 3 months of lost revenue.

It is unfortunate then, that pressure die-cast designers have never had the ability to appraise their die designs before the actual production tool is produced. This fact means that the effectiveness of a die design is only as good as the designer's empirical knowledge of the pressure die-casting process and Chapter Four has already shown the level of complexity involved in those processes.

Producing prototype castings to appraise a design only goes part of the way towards appraising the design of the tool itself. In fact, the Die-casting Development Council (1999[3]) state that *"the only certain way to fabricate a prototype casting with 100% of the properties of a pressure die-cast part is by actually pressure die-casting in the designated alloy"*.

In an attempt to address this problem, the United States Automotive Materials Partnership (USAMP) implemented a study in 1997 (NADCA, 1999[2]) to speed up the production of a pressure die-cast tool. The consortium sponsored Exco Engineering, Ontario, USA, to produce a full working pressure die-cast die which could generate 300 castings in aluminium alloy on their 3500 tonne Prince cold chamber high pressure die-casting machine.

3D Solid CAD modelling was used to generate the designs for the tool and Magmasoft FEM analysis software was used to verify thermal distribution around the die under working conditions. High Speed Machining was used to cut the die cavities and this negated the need for secondary finishing, save for powder-blasting to polish the tool. Concurrent Engineering practices were employed from the outset of the project to significantly reduce production leads times.

The finished die performed well within specifications and the project was hailed as a milestone success in pressure die-casting development. The project can be seen as the first implementation of a Rapid Tooling approach, ever, to the production of pressure die-cast dies. However, it must be pointed out that the die was no cheaper than a conventionally machined tool and the study was more of an attempt to bypass the prototyping stage altogether through the reliance on simulation software.

5.4 Laminate Tooling for Pressure Die-casting

Within the remit of Laminate Tooling, the author began exploring new applications for this technology in 1996. As previously mentioned in Chapter Three, examples of Rapid Tooling techniques for a variety manufacturing applications were well under way when this research began. There were, however, limits to the extent that this research had gone. These were based mainly on:

- Build volume
- Temperature limitations
- Moulding pressures
- Speed of production of a Rapid Tool
- Longevity and robustness of the tooling

Many applications, where Rapid Tooling could be applied, require tooling of considerable size. Most, not all, systems under development are limited to the size of tool which can be produced. For example, the sintering of steel powders (as in DTM's RapidSteel process and 3D System's Keltool process) produce very complex, robust and durable metal tools but with volumes no greater than 300×300×300mm.

Many Rapid Tooling processes produce tooling for the production of parts at low temperatures. In this case, low temperatures are defined as less than 200-250^{0}C and encompass most moulding processes up to and including injection moulding. A good example of this is the adaptation of 3D System's SLA process whereby stereolithography (ACES™ build) tools are mounted directly into injection moulding machines to mould a limited number of prototype parts.

There are also limitations in the pressures in which many current Rapid Tooling techniques can operate. Up to the commencement of this research, none of the current Rapid Tooling processes have been required to produce tooling working above 150-200MPa (this is approximately the working limit for high production injection moulding machines). In addition, many of the 'indirect' tooling approaches require no pressure to be placed on the tool (investment casting of RP models).

Speed of production is important in some applications and this is hindered by the various steps required in the 'indirect' processes discussed in Chapter Two. At the beginning of this research, few 'direct' Rapid Tooling processes existed.

Resilience and robustness are an important issue when considering a suitable Rapid Tooling process to generate multiple prototype parts or mouldings from. Most Rapid Tooling processes produce prototype parts or mouldings in similar materials to those required for production. Very few are required to be run on the actual production machinery to appraise the effectiveness of the tooling design, or required to handle the material used in the production environment.

Though laminate tools were successfully produced by the author for a variety of moulding applications, prior to this research, for various reasons the process was considered unsuitable. For example large metal laminate tools for thermoforming was considered excessive when compared to conventional wooden/polymer forms and many different Rapid Tooling processes are being modified for injection moulding.

In identifying and developing Laminate Tooling for different applications, the author came into contact with toolmakers from many different backgrounds. During this time a group of pressure die-cast designers made an enquiry about Rapid Tooling for applications far in excess of any of those considered previously. They needed tooling capable of:

- Producing parts greater than 500×500×500mm in volume
- Forming materials at temperatures between 500–1000^{0}C
- Working at pressures greater than 200MPa
- Mounting and running the tools on existing production machinery
- Costs of tooling significantly less than conventional tooling (by a factor of 10)

Through consultation with interested die-casting groups, it was realised that Laminate Tooling could offer a Rapid Tooling solution which simply was not available through any other process. A laminate tool is robust, scaleable, quick and cheap to produce and is generated directly from a 3D CAD model.

Probably the most important benefit of this approach was that it would be the first prototyping technique, ever, which would allow a prototype die to be run on the actual die-casting machinery used during full-scale production. This would overcome all the problems associated with conventional prototype moulding techniques in that a laminate die could, hopefully, perform as a full production tool, producing full castings in numbers found inconceivable by conventional prototype techniques. A laminate tool for pressure die-casting could be used for a variety task including:

- Appraisal of the design under production conditions.
- Assessment of heat transfer and shrinkage during cooling.
- Most effective layout of cooling channels.
- Effective gate and runner design.
- Exchanging laminates to introduce new features to the die.
- Exchanging laminates to change orientation of internal detail of the die.
- Multiple iterations before the final 'design freeze'.
- Faithful reproduction of die-cast parts for fit, form and function testing.
- Effectiveness of the ejection system in the production tool.
- Potential for using the tool for short production runs

Existing prototyping techniques attempt to reproduce the actual part which will ultimately be cast. At the time this research started, the implementation of Laminate Tooling would be the first attempt to prototype the dies themselves and can be considered a combination of both prototyping and 'direct' Rapid Tooling.

Chapter Two has shown how the concept of Laminate Tooling has been successfully applied to the field of injection mould tooling. Given the potential benefits that Laminate Tooling could offer the die-casting industry, the remit of this research was, therefore, to ascertain whether Laminate Tooling could be applied to pressure die-casting and what limitations would exist.

If successful, the process would enable not only cost and time savings in the design process for conventional production pressure die-cast tooling but also offer advantages, to the die producer, which have never been available through existing prototyping methods employed by the industry.

5.5 *Identifying the Potential Research Areas*

Based on previous experience and the current literature, there were certain areas which presented themselves as necessary for investigation in relation to Laminate Tooling for pressure die-casting. These are listed as follows:

1. The laminates in the assembly may twist or warp if not constrained sufficiently during the die-casting process. What is the optimum clamping methodology which still allows the benefits of Laminate Tooling to be realised and is there an optimum orientation of the laminates (vertical, horizontal or combination) for a tool used in pressure die-casting applications?
2. Conformal cooling and heating channels offer a key advantage in this process over conventional die production. What is the optimum design and position of these channels in a laminate tool?
3. Pressure die-casting dies, generally, require a high degree of finishing and polishing. How can this be addressed with the stepping that occurs on a laminate tool?
4. Where a thin up-stand feature within the die cavity is required in the design of a laminate tool, will a solid insert be required to replace it and, if so, how would such insert be anchored during casting?
5. In applications where high heat and pressure are present, should some form of bonding of the laminates be applied to resist leakage of coolant, allow secondary finishing,

prevent de-lamination and enhance rigidity of the die during casting?

6. Dependant on any up-stand features present within the die cavity, the individual laminates which make up these features will deflect dependant on the force, direction and impact of the molten alloy as it enters the die cavity. For a given material, what are the design limitations before deflection permanently deforms that feature and renders the die useless?

Of the potential research areas listed, there has been ongoing work carried out by both the author and other research groups. This is summarised in the following sections.

5.5.1 Prevention of Warping in a Laminate Tool

Dickens (1997) addressed many of the issues related to clamping laminates and laminate orientation for tools required for less strenuous applications such as the 'Simco project' described in Chapter 2. It was realised that if a laminate tool for pressure die-casting was to be constructed, many of the issues discussed in that paper would need to be re-investigated when applied specifically to pressure die-casting.

5.5.2 Conformal Cooling Channels

The area of Conformal Cooling Channels, through the implementation of Rapid Tooling techniques, is fast becoming one of the key attractions for designers of moulds and dies. Work began in the early 1990's by Sachs *et al* (1995) and continues today. Conformal Cooling Channels can be applied to all Rapid Tooling approaches currently under development and the problems of optimum design and location of the of the channel in a given tool are applicable to all moulding and tooling techniques. The findings of this work will be readily transferable to laminate tooling for pressure die-casting design.

5.5.3 Removal of Stepping

The issue of stepping within a laminate tool is an issue for all RP&T techniques. Prior to this work the author researched this field extensively. A technique was developed whereby the same 3D-CAD model, used to generate a laminate tool, was simultaneously used to form a solid stereolithography (SLA) model of the tool cavity which would ultimately need finishing. The SLA model was then coated with a conductive silver paint and electroplated with copper to a thickness of about 170 microns. This could then be used as an EDM electrode to remove the stepping in the assembled laminated tool as shown in Figure 5.2:

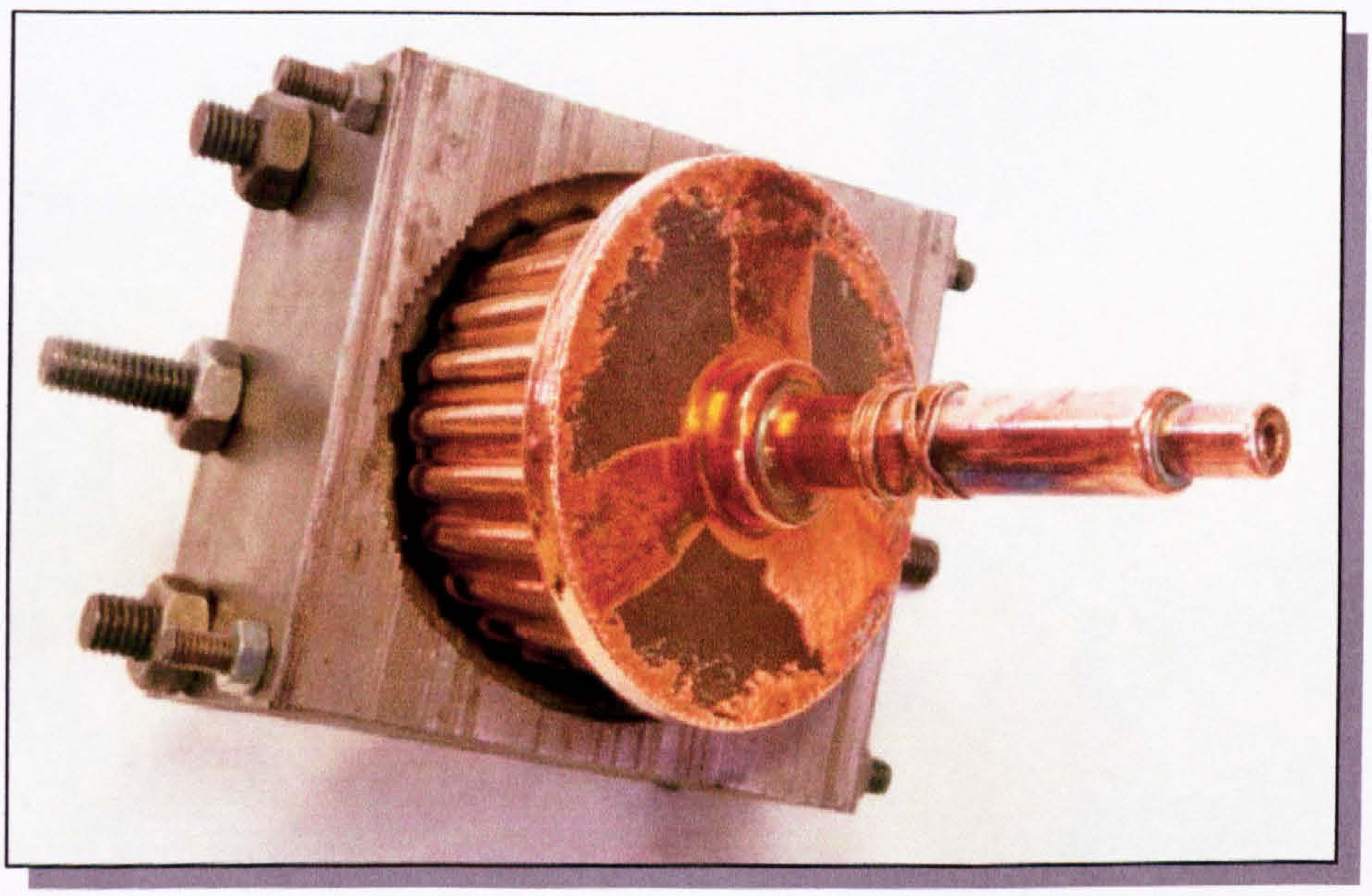


Figure 5.2 SLA-EDM electrode for finishing laminate tools

The tool became known as an SLA-EDM electrode (Soar & Dickens, 1996[1]) (Soar *et al*, 1997) and the concept has been taken up by other research groups around the world. The concept had limitations when it came to generating electrodes for large scale tools (>500x500x500mm) and current interest lies in using either High Speed Machining, to rapidly finish the surface of the tool, or Laser Ablation to both simultaneously remove stepping and weld the edges of the laminates in one operation.

5.5.4 Replaceable Solid Die Inserts

Where a laminate tool is constructed from horizontally stacked laminates, tall 'island features' within the cavity may be impossible to clamp (refer to Chapter Two Section 2.2.3). In such tools, it may be wise to substitute the laminates for solid metal inserts.

Some of the issues relating to the use of solid inserts for pressure die-casting applications were addressed with the work undertaken for the USCAR consortium. The work considered a horizontally stacked laminate assembly requiring tall narrow up-stand features which would have been impossible to incorporate as part of the laminate stack (Soar and Dickens[2], 1996). A stereolithography model of the insert is shown in Figure 5.3 and shows the solid replaceable inserts in the die cavity of the tool.

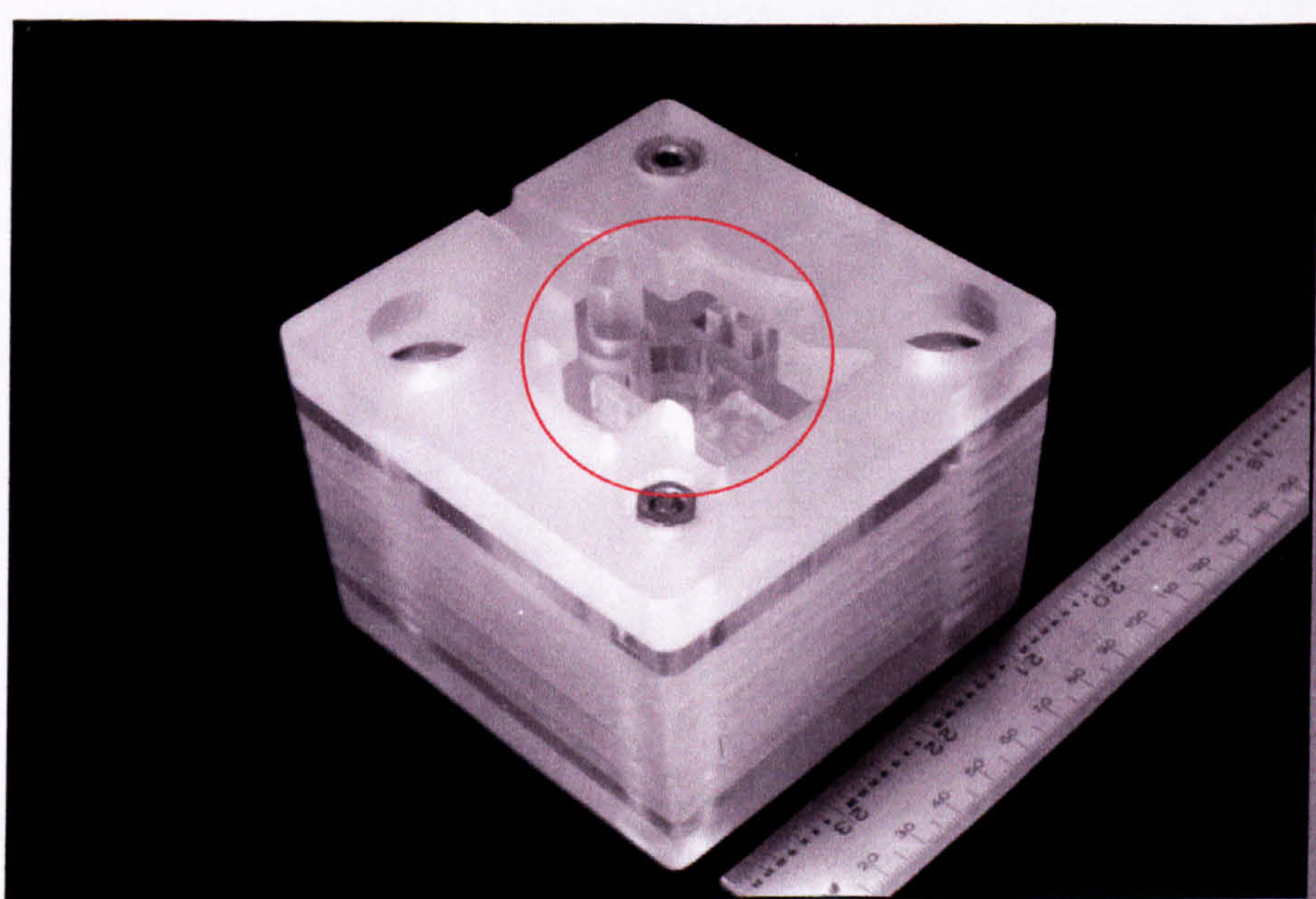


Figure 5.3 Exchangeable solid inserts for laminate tooling

5.5.5 Inter-Laminar Bonding

It is almost intuitive to consider some form of inter-laminar bonding essential if the entire laminate stack is to be expected to behave as a similar tool machined from solid stock. The author had already demonstrated the effectiveness of using high temperature epoxy resins to bond the laminates in the laminate injection-mould tool discussed in Chapter Three (Soar and Dickens, 1996[2]). However, this approach would almost certainly fail with the higher temperatures encountered in pressure die-casting as epoxy resins fail above 250^0C (Hergonrother, 1983) and a die cast tool would run well above this.

An extensive study was conducted by the author, in conjunction with GEC-Marconi, UK, to identify what problems could be expected when bonding laminates for a die-cast tool and how they could be over come (Bocking *et al*, 1997). The major finding of that work was the difficulty in finding a suitable bonding technique for Laminate Tooling in the pressure die-casting environment. The technique had to be scaleable, cost effective and resilient. Many soldering (bonding below 450^0C) and brazing (bonding above 450^0C) techniques exist but all present their own problems. Solders tend to work at too low a temperature for the pressure die-casting process and would fail. Diffusion bonding offers excellent bonding at high temperatures but the technique means that the bonding process (at around 900^0C) would take a steel sheet above its annealing temperature (at around 800^0C).

To address this, a novel and patented process was developed at GEC-Marconi (Bocking *et al*, 1997) which combines both soldering and diffusion bonding in one process and has become known as Diffusion Soldering. The process involves the pre-treatment of each laminate in the tool prior to bonding. Once cut, each laminate is cleaned to remove any scaling from the rolling process and electroplated with approximately 10μm of copper. Each laminate is then further coated with 2μm of tin. The laminates are then assembled and clamped to hold the laminates rigid during the heating process.

The laminates are placed in an evacuated furnace and the temperature is ramped over three hours to 676^0C where it is held for a further hour before cooling. During the heating cycle, the tin solder begins to flow at around 450^0C and reacts with the copper to alter its eutectic phase temperature and cause it to flow as an alloy of both tin and copper (Cu_3Sn). This is well below copper's usual melting point in excess of 900^0C.

The process continues, at the holding temperature, until the tin diffuses out of the alloy solution into the steel laminates either side. On completion of the cycle, all the tin diffuses out of the joint leaving a 99.9% pure copper bond between the laminates. Any attempt to re-melt the bond can only be done by taking the laminate stack upto the melting point of the copper (900^0C).

This innovative technique meant that the laminate stack was permanently bonded below the annealing temperature of hardened steel alloy and could operate well above the melting point of aluminium casting alloys (690^0C). In addition, the unique use of tin in the joint enabled very rough joints to be bonded completely due to its wetting ability during heating. All brazing processes require very flat and smooth bonding planes to form a perfect seal on the joint.

It was also discovered that the process allowed the laminates to be clamped with around 5MPa force which is an order of magnitude lower than brazing requires. Massive vacuum furnaces are now readily accessible (>500×500×500mm) making the process very scaleable. An SEM photograph of bonded 'M2 high speed steel' laminates at 1mm thick is shown in Figure 5.4.

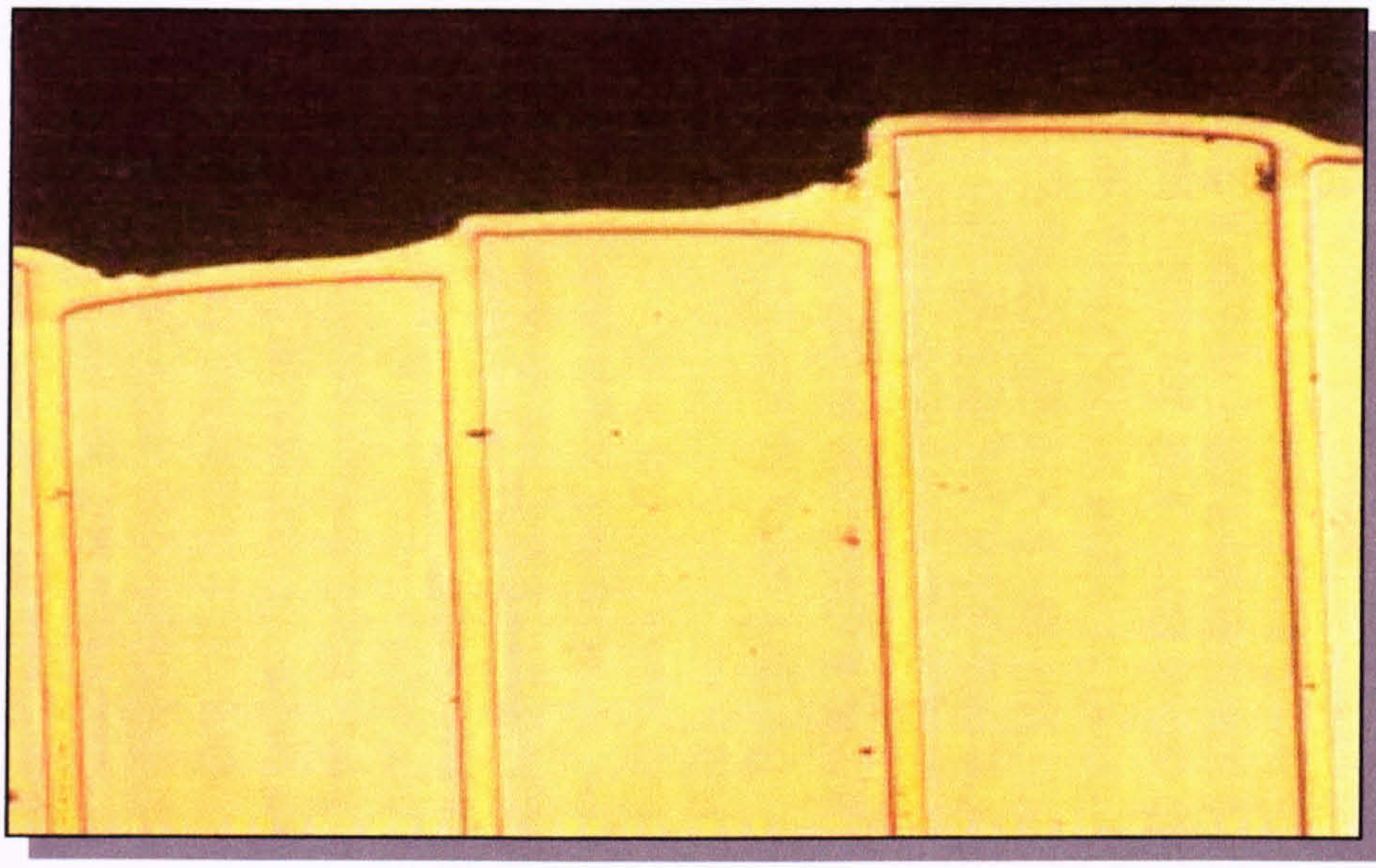


Figure 5.4 SEM photograph of diffusion soldered laminates

Adams and Wimpenny (1998[2]) are also studying brazing techniques for Laminate Tooling at the Rapid Prototyping and Tooling Centre, at Warwick University.

Experimental work was also undertaken by the author to find alternative high temperature bonding materials. The most promising being fused silicate glasses based on sodium silicate solutions and enamels. This work can also be found in the author's internal report for the USCAR consortium in Appendix I.

5.5.6 Deflection in a Laminate Pressure Die-cast Die

When Rapid Tooling, and, consequently, Laminate Tooling for pressure die-casting was being conceived, various groups began to consider ways to bond the laminates together. Bonding the laminates in the die in some way attempts to force them to behave as a standard machined tool from solid stock. If the laminates were to remain un-bonded then a completely different behaviour could be expected. Bonding the sheets, in a laminate tool, eliminates the flexibility of being able to insert new profiles when the tool design changes. This is important during the product development process before the design is frozen.

This raised the fundamental question of whether bonding was necessary in a (prototype) laminate pressure die-casting tool. If bonding were not required then there would be some significant advantages to be gained over bonding the laminates:

- The technique of diffusion soldering, though innovative, would add considerable cost to the production of a laminate tool and the concept of low cost tooling for design verification would be lost.

- Fixing the laminates in position, through bonding/welding etc., eliminates many of the benefits in being able to exchange and replace internal features of the laminate tool. The concept of laminate tooling is that multiple design iterations can be undertaken before the 'design freeze'.

- The time to produce the bonded laminate tool would increase, due to the specific problems associated with laminate preparation and coating prior to bonding.

- There is the possibility that the usual inclusion of ejector pins and sliding elements or cores within a die-cast die could be eliminated by using the laminates themselves to slide past each other to aid ejection of the casting.

- An un-bonded laminate stack, though constrained, acts less like a solid mass and more like a compressed spring. This gives the assembly a degree of resilience under the high impact conditions of pressure die-casting.

- Heat checking and crack propagation is common in conventional die-cast dies. The laminates in an un-bonded tool may act to arrest crack propagation along the die surface as the crack could not travel across a laminar boundary.

With an un-bonded laminate tool deflection of the laminates was envisaged to be an important area of research. Therefore, the scope of the research for this thesis was chosen as:

An investigation into the use of an un-bonded laminate tool for pressure die-casting. If this proved to be possible then the work would concentrate on the possible deflection of laminates within the tool.

5.6 Pilot study to Explore Deflection in an Un-bonded Laminate Tool

The previous section commented on the almost intuitive requirement for some form of inter-laminar bonding in a laminate tool when used in the harsh environments found in many moulding techniques including pressure die-casting.

To begin to examine whether this statement was true, there was the opportunity to use the laminate injection mould tool discussed in Chapter Three to explore some of the potential problems which may be encountered when constructing a laminate tool for pressure die-casting applications. This exploration formed the initial pilot study to this research and is described, as well as the issues that the study raised.

5.6.1 Introduction

In the development of Laminate Tooling for injection moulding, undertaken by the author, two identical moulds were produced. The first had all its laminates bonded with an epoxy resin to explore potential bonding techniques and the second tool was left un-bonded as a control for this work. Both tools were run extensively on an injection-moulding machine and both performed similarly under the conditions in that particular machine. For this study the second un-bonded tool is considered.

5.6.2 Methodology

The tool was designed with a tall narrow up-stand feature within the cavity. This feature was ovoid, on plan view, with vertically stacked laminates which were clamped at their bases.

This left the laminates which make the up-stand feature on the male half of the tool un-constrained and reliant on the effectiveness of the clamping at their base to impart rigidity to the tool during moulding. This meant that the laminates which made up the end sections of the ovoid feature were no wider than 2mm, were 0.5mm thick and 8mm tall.

To test the ability of these tall narrow laminates to withstand deflection and deformation during moulding, the flow of the incoming polymer was directed to strike these up-stand laminates 'end on' placing them under the greatest deflective load possible, as shown in Figure 5.5. The tool was then set up on the same injection-moulding machine, as in the previous experiments. Six shots were taken whilst progressively increasing the temperature of the polypropylene (to reduce its viscosity) and the pressure, exerted on polymer, up to the maximum the machine could offer. The objective being to establish whether these narrow laminates at the end of the up-stand feature could be, at least, deflected away from the remaining laminates in the feature, or even snapped off.

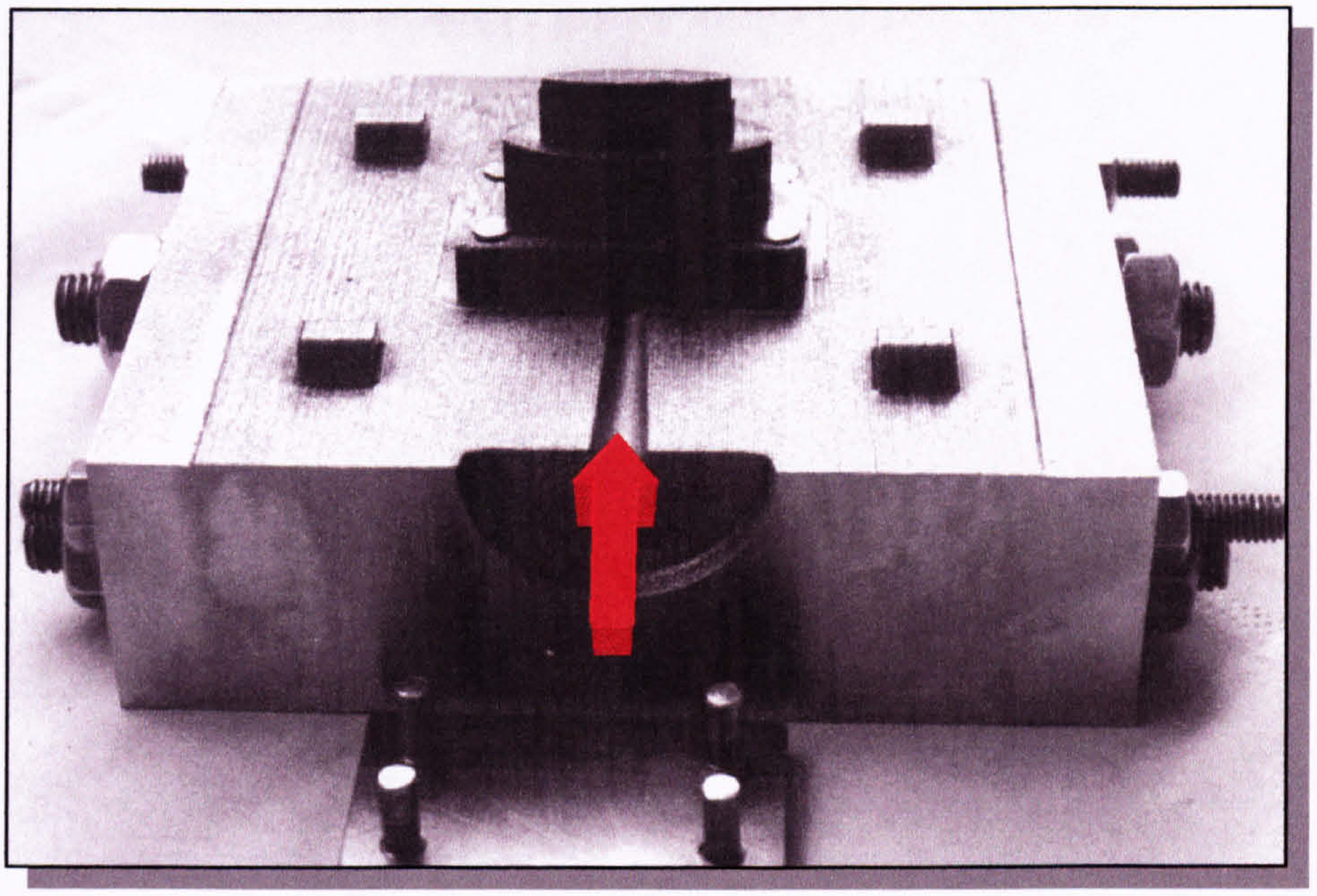


Figure 5.5 Orientation of flow to laminate stack in tool

5.6.4 Results

The first shot was done with the tool at room temperature. After each shot the heat within the tool was allowed to accumulate up to 80^0C by the last shot. The maximum temperature possible for the polypropylene was 220^0C (well above moulding temperature) and the maximum pressure exerted on the polymer in the shot chamber being 19MPa. At these temperatures and pressures, the polypropylene has the viscosity of water and was crystallising into a brown mess by the last shot.

Upon removal of the last moulding, the laminates were examined and showed no signs of either permanent deformation or ingress of polymer between the un-bonded laminates.

5.6.5 Discussion

An un-bonded laminate structure readily withstands the conditions present in injection moulding. There are, however, fundamental differences between injection moulding and pressure die-casting which first needed to be identified before this research could begin.

5.7 Assumptions

In order to study the effects of pressurised molten alloy on an up-stand feature in an un-bonded laminate pressure die-cast die, it was first necessary to identify the potential effects which may be encountered through the deflection of laminates in such a tool. The following assumptions and were drawn through the interviews with Birch and Poppa (1997). They identified the following effects that may be at work in an un-bonded laminate die:

- Entrapment of the casting.
- Pressure equalisation during 3rd phase compaction.
- Effects of fluidity and wetability of die-casting alloys.
- Other issues.

5.7.1 Entrapment of the Casting

Entrapment, in the case of an un-boned laminate die-casting die, is defined as the movement of individual laminates, in an up-stand feature, away from the vertical plane. This 'splaying' effect creates an undercut on the male features in the die which would result in the casting seizing to the ejector half of the die. This would, essentially, render the die unusable as, even if the casting could be forced off the feature those laminates at the end of the feature would be permanently damaged as demonstrated in Figure 5.6.

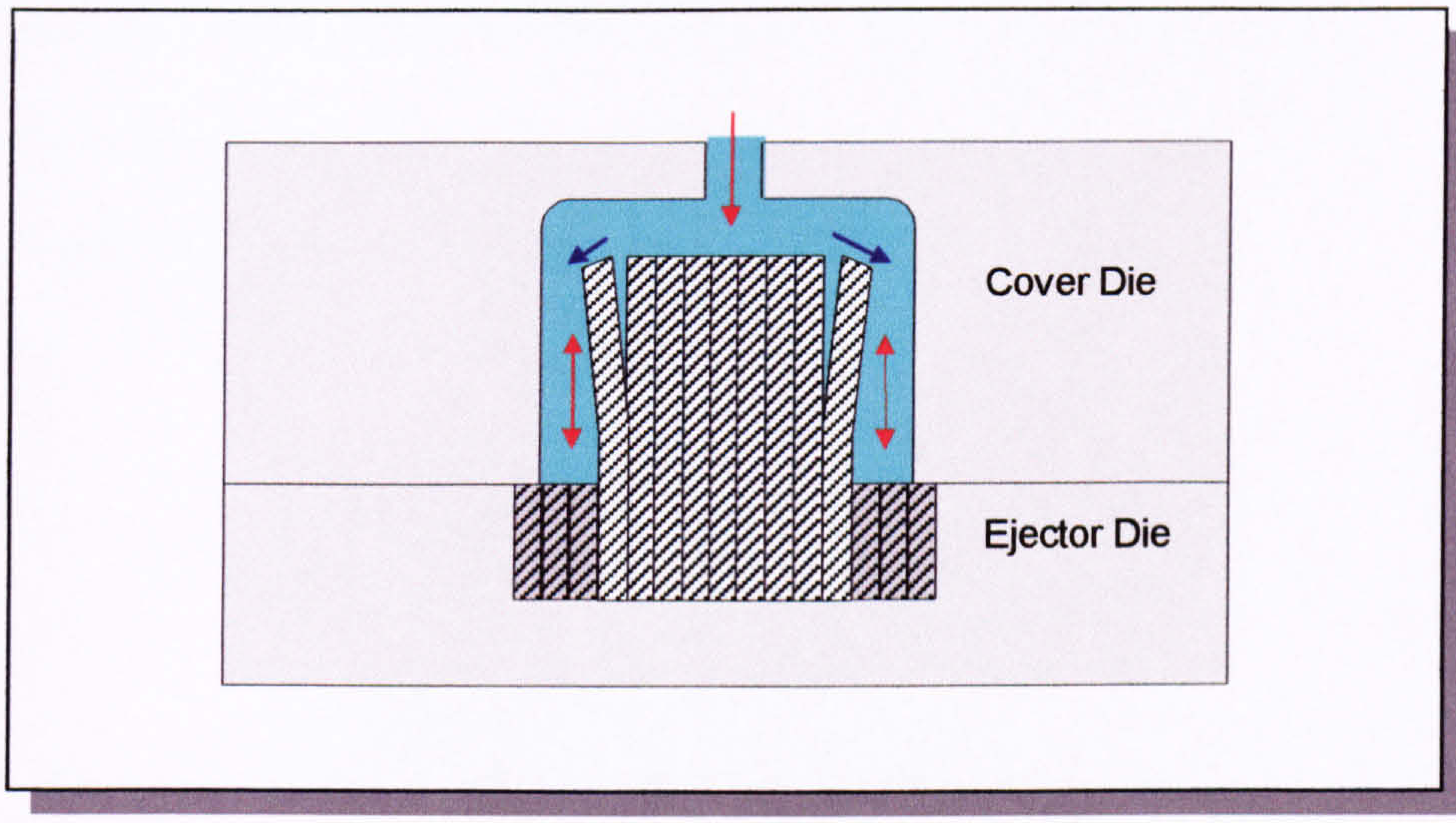


Figure 5.6 Effect in incoming alloy into laminate die cavity

With all pressure die-cast dies (except Squeeze Casting where no runner exists) the molten alloy approaches the die cavity via a runner and inlet gate along the parting line of the die. The runner directs the flow of alloy away from the shot sleeve and through the inlet gate which is shaped to distribute the alloy evenly around the die. The runner and inlet gate are cut into the cover die along the parting line so that the casting and slug (solidified alloy left in the shot sleeve and runner) come away from the die as one piece when the die is opened.

This is unlike the injection moulding process where material is commonly forced into the mould cavity from above, as was shown in Figure 5.5. This is an important difference, as splaying would not occur in Figure 5.5 if the molten alloy entered the die cavity along the parting line of the two halves of the tool. In pressure die-casting, what may force the laminates to splay is if the flow of alloy were to enter the die 'end-on' to the laminates in an up-stand feature, as in the injection mould tool pilot study, but, again, the width of the laminate then comes into effect to prevent deflection.

Even with the 0.5mm thick laminates, used in the un-bonded injection mould tool, the laminates had enough width, 'end-on', to withstand deflection by the incoming polypropylene. Within pressure die-casting, the worst case scenario, therefore, is when alloy enters along the parting line of the die and enters the die cavity 'side-on' to a laminate up-stand feature as shown in Figure 5.7.

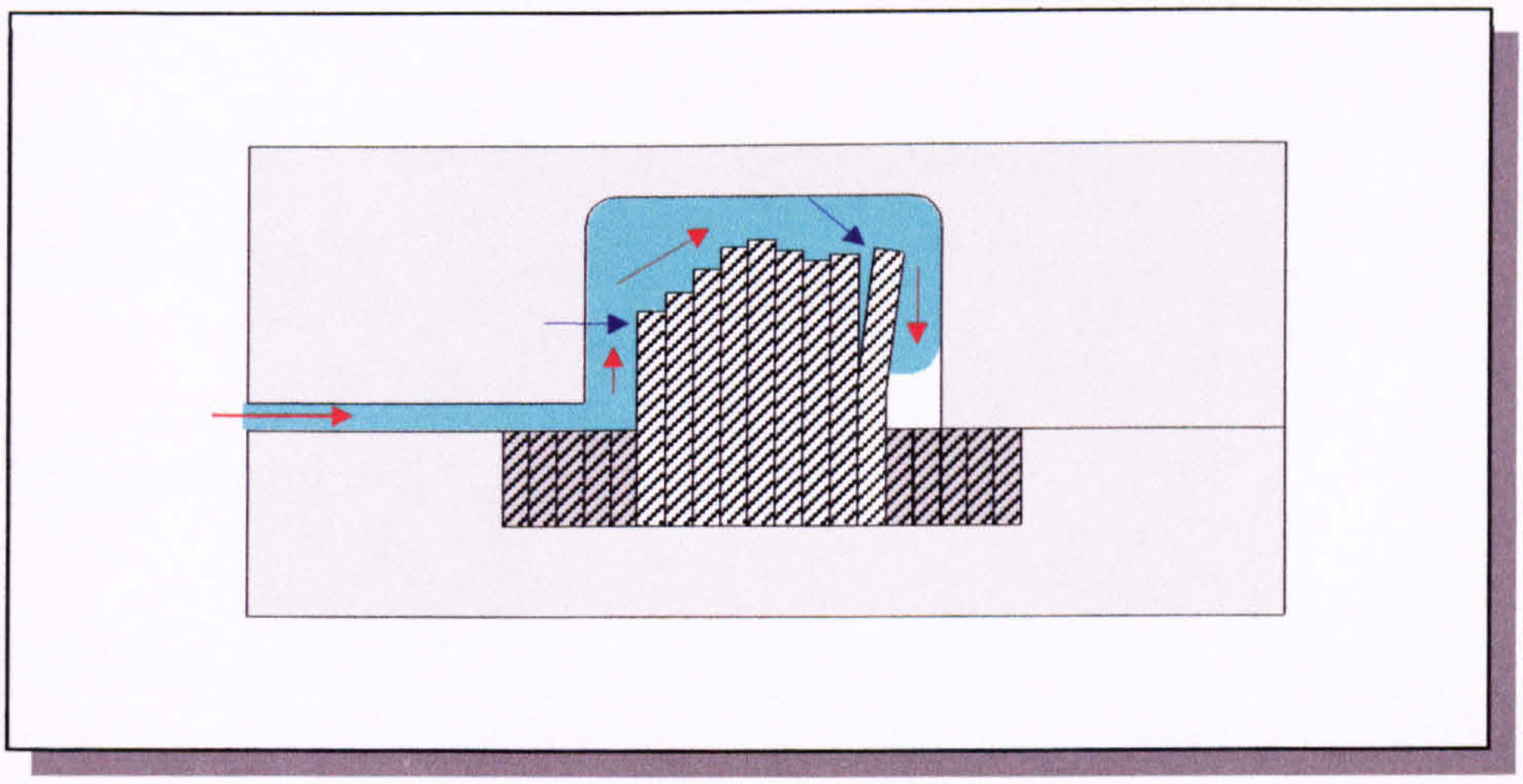


Figure 5.7 Effect of alloy entering laminate die cavity

The alloy will be forced up over the feature (red arrows denote flow) and, depending on the design of that feature, impinge on the laminate farthest away from the point of entry of the alloy. If this last laminate should protrude slightly above its neighbours then it will receive the force of the incoming alloy and be deflected away from its neighbours (blue arrows denote force).

There are two scenarios which could occur at this stage, assuming that the laminate's modulus of elasticity (Young's modulus) and Ultimate Tensile Stress (UTS) is high enough to withstand being simply bent over or snapped:

1. The laminate is deflected away from its neighbours allowing molten alloy into the gap between the laminates. Once the die is filled, the alloy solidifies with the laminate

permanently deformed leading to entrapment of the casting.

2. The laminate is deflected away from its neighbours, ingress of alloy occurs in the gap, the die fills completely, the pressure equalises in the cavity and the gap closes as the laminate springs back to its upright position before the alloy solidifies, pushing the alloy out of the gap.

Both of these scenarios are equally possible and are best explained by considering the unique circumstances which occur in pressure die-casting.

5.7.2 Pressure Equalisation after 3rd Phase Compaction

In pressure die-casting, there is no exit for molten alloy to escape once the die is filled. Small vents allow the escape of trapped gasses as the die fills but are too narrow for alloy to pass down. The alloy will attempt to pass through a vent, due to the pressures at work, but as soon as it enters the vent its heat is drawn into the surrounding die and its fluidity (viscosity) increases effectively sealing the vent off.

This sealing off of any gaps, or vents, creates a sealed cavity in which the full effect of 3rd phase compaction can take place. Consider, then, the deflected laminate in Figure 5.6. It is only natural to assume that we are dealing with a 'static' load or 'bending moment' acting on that laminate. This is the force exerted by the incoming alloy on the laminate around the point at which it is anchored to the surrounding laminates which support its base. If the cavity were open ended and a constant flow (dependant on velocity) of alloy were striking the top of the laminate, then there would be a bending moment and calculable deflection on that laminate.

Die-casting is 'dynamic' (as defined by Beam Theory). As the molten alloy is forced over the up-stand feature, it will impart a deflective force on the end laminate only until the die cavity fills. It is not the pressure exerted on the molten alloy which causes the laminate to deflect but the velocity of the alloy flowing over it. As soon as the die is filled this velocity reduces to zero and the forces acting on the laminate equalise on both sides of it as shown in Figure 5.8.

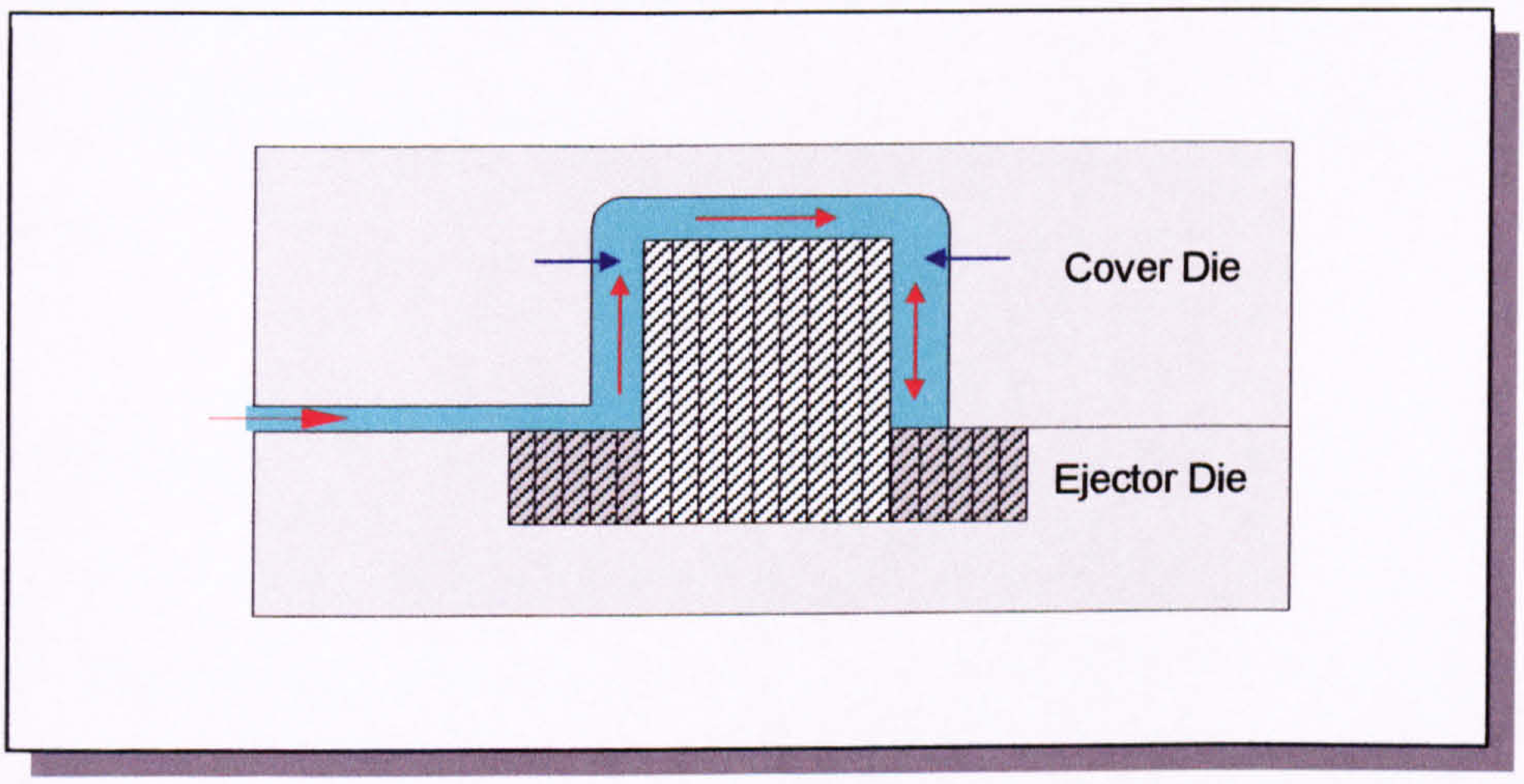


Figure 5.8 The effect of pressure equalisation within the die cavity

There will always be some deflection within an un-bonded laminate up-stand feature and it can be assumed that if a large enough gap opens up between the laminates in that feature some ingress of alloy will occur into the gap. The question is, therefore, if the end laminate does deflect during filling and ingress occurs, will there be enough time before the alloy solidifies for the laminate to spring back into its vertical position thus forcing the still molten alloy out of the gap?

If it does not, the alloy will freeze around the deflected laminate leaving it in a 'splayed' position effectively forming an undercut which the casting cannot be ejected from. This is possible due to the rapid chilling which may occur on any molten alloy forced down a cold (the die is always cooler below the die surface) gap between the laminates.

5.7.3 Effects of Fluidity and Wetability of Casting Alloys

If the alloy does not solidify instantly and there is sufficient heat in the alloy to allow the deflected laminate to spring back, will there be traces of alloy left between the laminates which would affect the tolerances and dimensions of that up-stand feature?

The answer to this problem lies in the 'fluidity' of molten alloys in the pressure die-casting process. 'Fluidity' is a term unique to metal casting where the usual term 'viscosity' is inappropriate.

Most stable liquids behave in a uniform or homogenous manner in that they have a certain viscosity over a range of temperatures which are consistent in any application. This includes thermoplastics in the injection moulding process whose viscosity changes as it enters the cool mould. Even with a rapidly changing viscosity due to heat dissipation through the die, this change is still constant and calculable. With casting alloys and metals this does not apply, for the simple reason that other factors affect a molten alloy's viscosity apart from the rate of heat dissipation into the die.

As molten metal alloy passes through a mould, or die cavity, it is reacting with oxides, release agent on its surface, as well as any gasses it encounters, and any impurities it picks up along the way. In addition, as the 'flow-front' of the alloy passes through the die, the drop in temperature changes its structure from a smooth liquid to a course granular 'slush'. In order to describe this behaviour, the term 'fluidity' is used to describe the non-uniform behaviour of molten metals. Casting alloys are tested by pouring the alloy through a hollow coil held at an exact temperature and then measuring how far the alloy proceeds through the coil before it freezes.

The Metals Handbook (1996) states that, though difficult to calculate, molten aluminium alloy (LM24) has been shown to have a similar viscosity to water at casting temperatures. The measurement for viscosity of molten alloys has to be conducted at a constant temperature above the alloy's melting point, in a controlled atmosphere within a furnace, and does not necessarily reflect the behaviour of the alloy in a die-casting environment.

Birch & Poppa (1997) both observed that the flow front of the molten alloy is more viscous than its interior, by this definition it behaves more like treacle or syrup than water. In addition, they both commented on a die-cast alloys poor 'wetability'. Wetability relates to a fluid's surface tension. Two liquids with identical viscosity but different surface tension will not flow down the same gap between two surfaces. The classic example is that of water and mercury. Water is a very wetable liquid capable of flowing into a gap of less than a millimetre (particularly when aided by capillary action) whereas mercury will not, due to its strong surface tension. Kalpakjian (1992) observes that the oxide film on the surface of molten aluminium will triple its surface tension and that is without taking into account any 'chilling' that increases this figure further. Both experts observed that molten alloys behave very similar to mercury.

To test this, molten aluminium alloy was poured into the female half of the un-bonded laminate injection-mould tool, previously discussed, to see if un-pressurised molten aluminium could work its way into the very fine gaps between the laminates on that tool. The mould was pre-heated to 750^{0}C, well over the melting point of the aluminium alloy, to eliminate the effect of chilling of the alloy during casting. The tool was held at 750^{0}C for an hour, to give the alloy time to work into any gaps in the laminates. The casting was cooled and removed and is shown in Figure 5.9 and clearly shows a smooth finish indicating that no ingress of alloy occurred between the laminates. As with mercury, the alloy simply floated over the surface of the mould and would require some pressure to the alloy, to flow between the laminates.

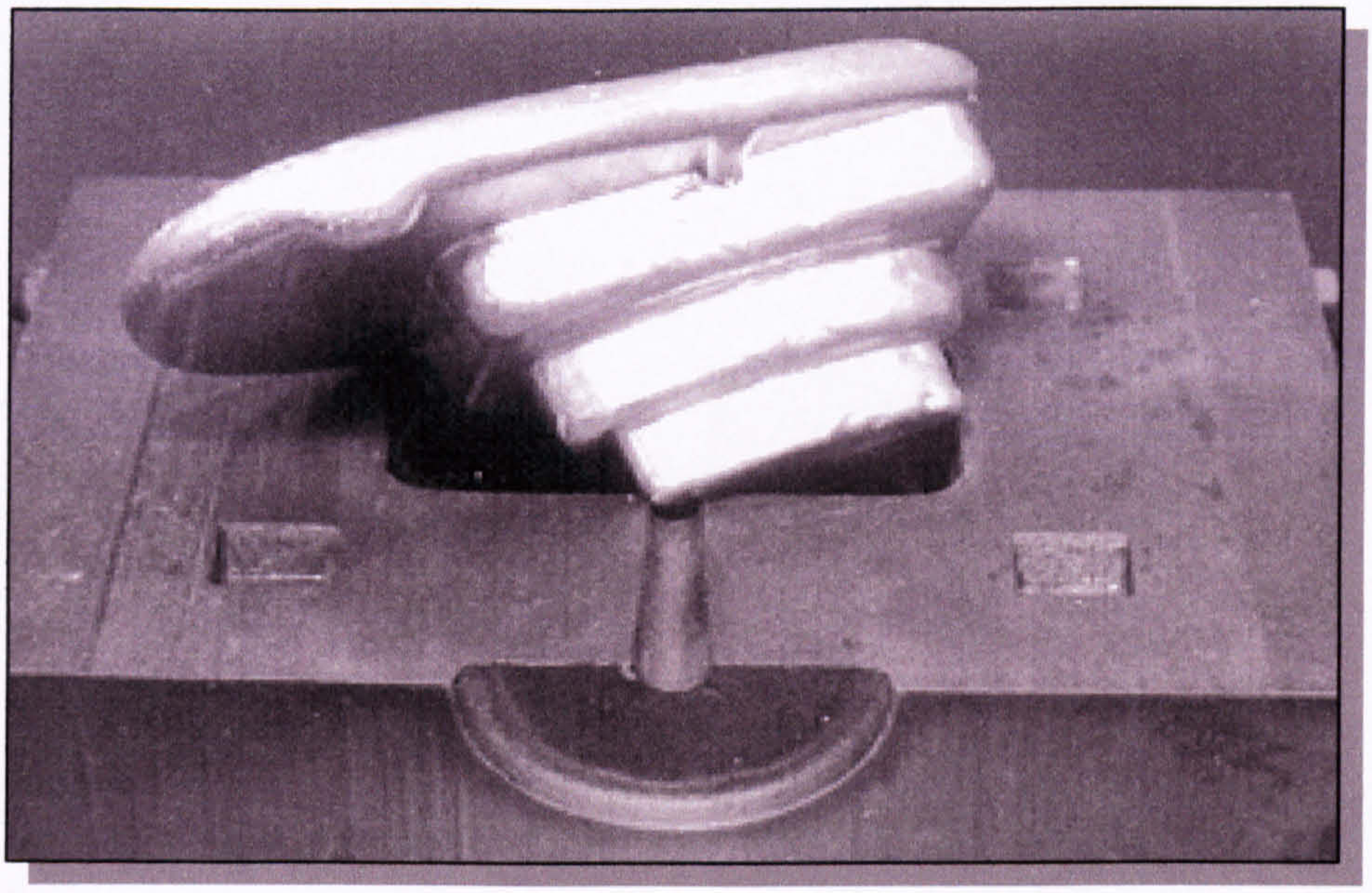


Figure 5.9 Demonstration of the fluidity and wetability of LM24

The conclusion of this test was that, if a small gap were to open up between the laminates in a laminate pressure die-cast die then the high surface tension of the alloy may mean that no alloy would travel down into the gap between the laminates. This implies that even if deflection, and even a small amount of ingress, does occur in the un-bonded laminates in an up-stand feature then the casting and the laminates in the die may remain unaffected as long as deflection does not exceed a certain amount.

5.7.5 Further Effects of Note

Should the design of the laminate pressure die-cast die ever include an isolated laminate (forming a narrow channel in the casting for example) then, again, assuming its modulus of elasticity and UTS are sufficient to avoid permanent deformation, the laminate will certainly deflect as alloy is forced around and over it, but this deflection will cease as soon as the alloy stops moving and 3rd phase compaction is initiated. Though brief, compaction is always initiated after the alloy has ceased moving and the alloy is still molten. During this time, there will almost certainly be enough time for the laminate to resume its original position before solidification.

Laminates located deep within an up-stand feature will also be deformed but will slide past each other much as a stack of cards slide over each other when the stack is twisted, with no gap opening up between them. Should any protrude above their neighbour then the same issues apply as above.

Laminates located at the end of the up-stand feature which face the flow of alloy entering the die will receive an even force from the alloy along their entire length. This effectively pushes the laminate against the laminates behind it and so offers resistance to deflection but, more importantly, eliminates any chance of ingress at this point.

From these assumptions the following hypothesis was drawn:

For any given sheet material, used in an un-bonded laminate pressure die-cast die, there is a design limit, over which, the laminates, which form an up-stand feature, will deflect and suffer permanent deformation and damage.

Chapter Six will, therefore, discuss the requirements for an experimental laminate pressure die-cast test-die to explore these possible effects further.

Chapter 6: Experimental Methodology

6.1 Aims and Objectives

The overall aim of this research, highlighted in Chapter One, is to investigate the feasibility of Laminate Tooling for pressure die-casting applications. This will be explored through two objectives:

Objective One

To establish whether an un-bonded laminate tool can be designed, constructed and then run on a pressure die-casting machine to allow the production of multiple castings from that die.

Objective Two

If the tool can successfully withstand this process, then a closer study of the design limitations will be undertaken when constructing such a tool, through analysis of the potential deflection in those laminates during the casting process which may result in their premature failure.

6.2 Identifying the Variables

For any laminate die design, the amount of deflection experienced by an up-stand feature will depend on a series of variables. In order to observe just the one variable (i.e. deflection), all the remaining variables had to be identified and set. These include:

- The alloy which will be cast.
- The pressure die-casting process to be used.
- The die material to be used.
- How deflection will be measured.
- The design of the test-die.

6.2.1 The Casting Alloy

The casting alloy chosen for this research was Al-Si8-Cu3 or LM24, in the UK, ((BS1490) /A380 (ASTM)). This alloy is used globally for pressure die-casting, due to its alloying elements which lend it to the process. Its properties are shown in Table 6.1.

Tensile strength (6 mm dia. test pieces)	300 N/mm^2 (20 tons/sq in)
Tensile strength as cast	150-170 N/mm^2
0.2% proof test	120-150 N/mm^2
Elongation	1-3%
Expansion Coefficient	2.3×10^{-5} per ^0C
Fatigue properties	±50-100 N/mm^2 (5×10^7 cycles)
Specific Gravity	2.8

Table 6.1 Properties of die-casting alloy LM24

6.2.2 The Die-casting Process

The selection of LM24 as the casting material also set the second constraint. LM24 can be pressure die-cast by all the casting processes discussed in Chapter Four, except the hot chamber High Pressure Die-casting (HPDC) process used for zinc and magnesium alloys. This left a choice between cold chamber HPDC, the Low Pressure Die-casting (LPDC) processes and Squeeze Forming. The latter two choices were discounted, primarily due to the cost of this developmental equipment and its lack of availability. This left cold chamber HPDC, which is the most prevalent process used in the industry. It also has the highest operating pressures of all the pressure die-casting processes and if an un-bonded laminate tool could withstand it then it could be applied to all the remaining processes.

For an effective experiment, the laminate test-die had to be mounted on a production pressure die-casting machine. As the University of Nottingham (where the research began) possessed no such facilities, various companies and research institutions were contacted both here in Europe and the USA.

Certainly, no die-casting company in the Midlands was able to offer free time on their machines, as they are kept at maximum capacity to ensure the recovery of their high costs. GM's Saturn Plant offered the use of a machine in Nashville, USA, but the distance was too great. Finally, one machine was located in the Mechanical Engineering Department at Aston University in Birmingham, England.

The machine was an EMB 100(10b) pneumatic 'horizontal' cold-chamber HPDC machine. This particular model was manufactured just outside Birmingham by EMB Ltd, in 1960, and was one of their most popular models of the time. It is by no means a large machine, the clamping force is 100 tonnes, compared to some of the large machines which go up to 3000 tonnes clamping force. The machine is now considered quite outdated in that all new machines use the more controllable hydraulic actuators, but it was sitting idle and was deemed suitable for a feasibility study of the concept of laminate tooling for pressure die-casting. Specifications for the machine are shown in

Table 6.2.

Die Locking Force	75 Tons (UK)	76 Tonnes(Metric)
Distance Between Ties	10" by 10"	254 by 254 mm
Dia. of Tie Bars	2"	50.8 mm
Size of Moving Platen	16" by 16"	406 by 406 mm
Max. Die Height	13"	330 mm
Min. Die Height	5"	127 mm
Die Opening Stroke	6"	152 mm
Shot Position	Centre and 3" offset	76.2 mm offset
Weight per Shot (Al)	.65 lbs	.29 kg
Volume per shot	6.5 ins^3	106 cm^3
Dia. Of Inj. Plunger	1.25"	31.8 mm
Total Force on Plunger	11,775 lbs	5,334 kg
Max. Pressure on Metal	9,600 lbs/in^2	66.12 MPa
Full Stroke of Plunger	8"	203.2 mm
Min. Dry Cycle Time	4 secs	4 secs
Compressed Air Pressure	150 lbs./sq in.	1.055 MPa
Max. Free Air per Shot	15 cu ft	425 litres

Table 6.2 Specification for the EMB 100 HPDC machine

6.2.3 Die Material Selection

Selection, location and purchase of a suitable sheet material from which to construct the laminate test-die proved a central part to this study. Such a material would need to satisfy the following criteria:

- Match the properties of existing die steels.
- Withstand permanent deformation.
- Define as much detail as possible in the die.
- Have adequate hardness.
- Have adequate resilience to resist heat checking.

- Have consistent thickness.
- Suitability for laser profiling.

All these issues had to be addressed individually. The sheet steel used, up until this point for the laminate injection mould tool was a high carbon (0.7-0.9% CS70) 'spring steel' which was available 'off-the-shelf' and in almost any thickness down to 0.25mm. This material has excellent hardness and resilience and was an initial choice.

Samples were exposed to molten LM24 but suffered excessive de-carburization, whereby the high temperature of the LM24 caused a migration of the carbon out of the steel which reacted with the surrounding oxygen in the atmosphere to form CO_2. This action deposited the carbon from the steel in the form of heavy scaling on the surface of sheet and reduced the thickness of each sheet by approximately 5%. This left the sheet steel with a diminished carbon content and therefore reduced hardness (samples were measured down to around 25 Rockwell C from the initial 48 Rockwell C).

This was a serious set back and resulted in an appraisal of a variety of sheet metals with varying alloying content which could resist the effects of carburization. This work was undertaken with the USCAR consortium, mentioned previously, in America, who had developed a specific test (the Wallace 'dunk-test') for materials used in die-cast dies. This work is shown in Appendix II.

The culmination of this work concluded that, where aluminium pressure die-casting is used, there is generally considered to be only one type of steel which is suitable for a pressure die-cast die. This is H13 'hot work' tool steel (BH13 in the US). There were many other suitable candidates (H10, M2, maraging steels etc) but none are as widely used or specified by the die-designer for die production as H13. The properties of this material are shown in Table 6.3.

Modulus of Elasticity at *20, 500 & 600^{0}C*	215, 176 & 165 x 10^3 N/mm^2
Thermal Coefficient *100, 200, 300 & 400^{0}C*	11.5, 12, 12.2, 12.5 x 10^{-6}m/(mK)
Thermal Conductivity at *20, 500 & 600^{0}C*	25, 28.3 & 29.3 W/(mK)
EN/DIN	X40CrMoV5-1 (EN24)
Hot Forming Temp.	1100-900^{0}C
Annealing Temp.	750-800^{0}C
Stress Relieving temp.	600-650^{0}C
Hardness after Hardening Rc	50-54
Tensile Strength at *400, 500 & 600^{0}C*	1300, 1100, 800 N/mm^2
0.2 % proof stress at *400, 500 & 600^{0}C*	1100, 900, 600 N/mm^2

Table 6.3 Properties for H13 'hot work' tool steel

Although H13's composition has remained constant through the century, the processing and production of the material has changed significantly, leading to a material with higher thermal fatigue resistance, reduced carbide grain size, increased homogeneity and reduced impurities. The chemical composition of H13 is shown in Table 6.4.

GRADE	Chemical Composition (average values, %)						
	C	Si	Mn	Cr	Mo	Ni	V
BH13 (W302) (X40CrMoV5-1)	0.39	1.10	0.40	5.2	1.4	-	0.95

Table 6.4 Chemical composition of H13 'hot work' tool steel

With the sheet material defined, it was then necessary to decide what thickness it should be. The trade-off is between the degree of finish and detail required in the assembled laminate tool against the assembly time, availability of the material and its ability to withstand permanent deformation during die-casting.

The fastest way to build a laminate tool would be to use very thick sheet material, say

25 mm (1"). As Figure 6.1 shows, if the sheets are thick they will resist deflection but then all the detail is lost and secondary finishing becomes 90% of the job to complete the tool. The other extreme is to construct the tool from metal foil. The detail would be almost perfect but the tool would be very difficult to assemble and an individual foil laminate would not withstand deflection during casting without permanently deforming.

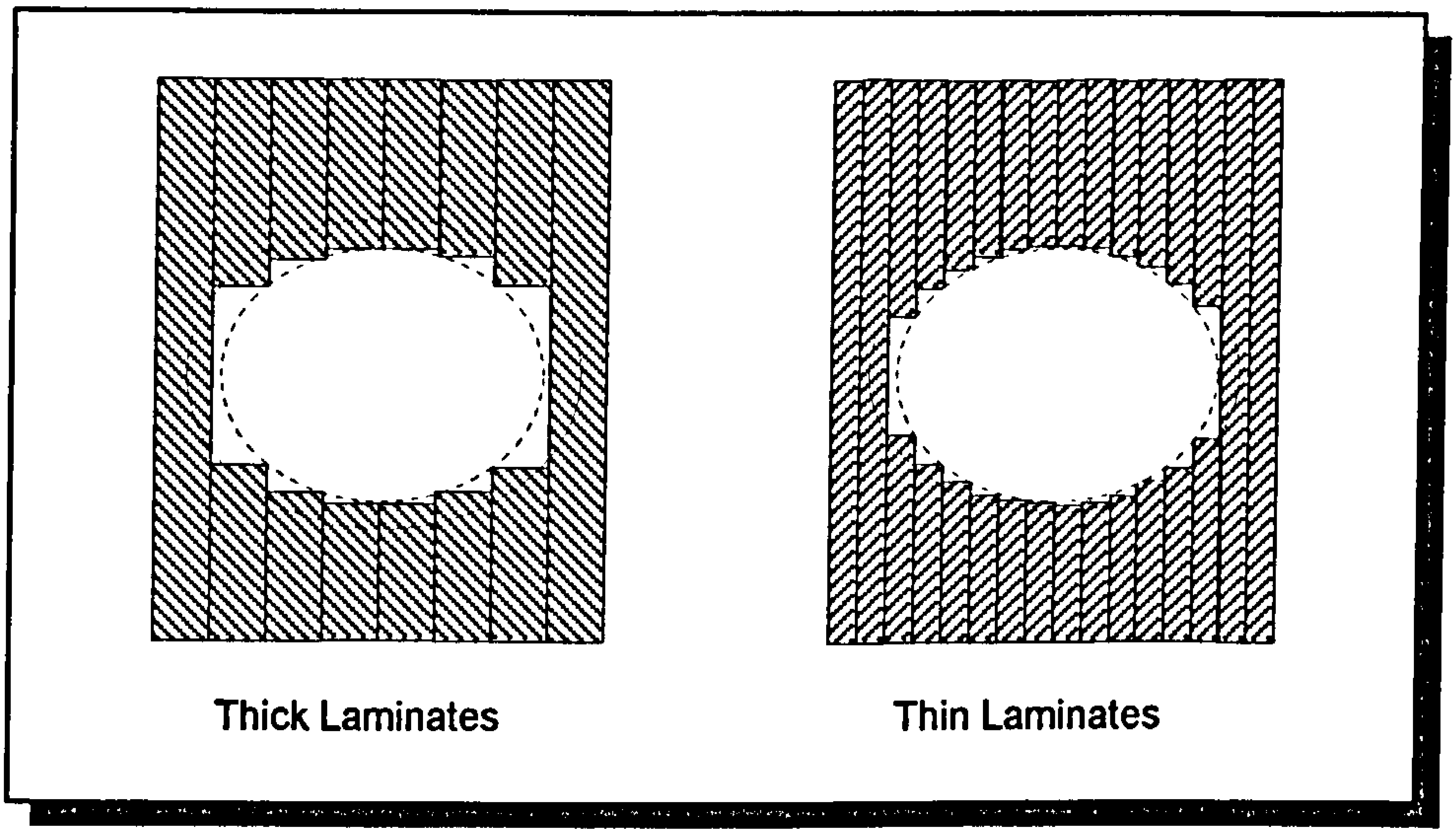


Figure 6.1 Trade-off between thick and thin laminates

An extensive search to locate rolled H13 sheet initially drew a blank. Similar materials are rolled into sheet, and Appendix III shows the work done to test similar materials of differing thickness to ascertain the optimum thickness of H13 which would best suit the criteria set out above.

Two suppliers were eventually located, CS Engineering in Japan and Böhler GmbH in Austria. Both companies specialise in hot and cold rolling of high alloy steels, such as M2 High Speed Steel (used for cutting and surgical blades), and both roll down to a minimum of 1mm thick.

In effect, the simple fact that they could not roll tool steel to less than 1mm cut the entire selection of an optimum sheet thickness short. Originally 0.5mm sheet steel (as in the injection mould tool) was considered to be close to the optimum thickness capable of withstanding permanent deformation during die-casting. The 1mm H13 sheet steel was a suitable compromise to reduce stair-stepping and secondary finishing. Rolling steel this thin improves the grain structure and alloy distribution over forged billet, but it does set up stresses in the sheet which must be relieved later during final hardening and tempering of the tool. Batches of cold rolled and hot rolled sheet were ordered from CS Engineering and Böhler which took almost six months to appear.

Tests were conducted on the two 1 tonne batches which were delivered from both mills. They arrived in the annealed condition (24-28 Rockwell C). Samples were cut from three sheets in each batch for Ultimate Tensile Stress verification against their stated figures of $1000N/mm^2$ at 400^0C. These first required hardening and tempering and worries over carburization during hardening were overcome by using an evacuated furnace which prevented any interaction with oxygen during hardening and tempering. The laminates were heated to 1020^0C, in a partial vacuum for 7 hours, then nitrogen gas quenched before double tempering at $600\text{-}610^0C$ for a further 5-6 hours.

The average measurement (at room temperature), after hardening to 54-58 Rockwell C, for three planes (with, across and 45^0 to the grain) being $1170N/mm^2$ for the hot rolled sheet and $1300N/mm^2$ for the cold rolled sheet.

The next test was to cut samples with the CNC laser profiler. Laser cutting leaves a narrow heat affected zone which can lead to embrittlement on the edges of each profile.

When stacked, these edges would make up most of the surface detail in the test-die. The laser profiler was a 1.5 kW CO_2 laser owned by a local contractor.

Samples were cut, in the annealed condition, then potted and polished for micro-hardness testing. Details are summarised in Table 6.5.

Distance from laser cut edge	Hardness Vickers (*HV*) and Rockwell C (*HRC*)
0.005 mm	735 *HV* - 63 *HRC*
0.025 mm	642 *HV* - 57*HRC*
0.100 mm	410 *HV* - 40 *HRC*
0.500 mm	408 *HV* - 40 *HRC*

Table 6.5 Micro-hardness readings as distance from laser cut edge

This increase in hardness, closest to the laser cut, is typical for laser cutting of steel sheet through the generation of a heat affected zone (Arata *et al*, 1979) (Schreiber and Clyens, 1993), the zone reaching to a width of approximately 0.5mm from the surface of the cut. The hardness readings for the cut, itself, are close to the fully hardened sheet steel required later. These results are analogous to the surface hardness left during EDM finishing of die-cast dies.

The final analysis to be conducted on the H13 sheet was to check for thickness variation. It was explained, in Chapter Two, that it is critical to know the average thickness of the sheet steel before the 3D CAD model is sliced and the data sent to the CNC Laser cutter. The cold rolled sheet which came from Japan showed an excellent surface finish, with no scaling, and is typical of the cold rolling process. The absence of heat requires far higher pressures to roll the sheet but imparts a very fine grain structure, flatness and high strength (Green, 1996). Its only drawback is the stresses which are set up on the sheet which can force laminates to distort. This only strengthens the argument for adequate clamping and support.

Hot rolled steel, on the other hand, is rolled in its 'cherry red' state. It requires much lower pressures and is cheaper because of this. The sheet emerges fully annealed, which relieves any stresses imparted during rolling. The hot rolled sheet was more distorted due to this stress relief, during rolling at 1mm, and the quenching which is required results in a layer of scale to a depth of around 0.05mm.

For the two sets of sheet the cold rolled sheet showed a mean thickness of 1.045mm with a range of 0.060mm. The hot rolled sheet showed a mean thickness of 1.043mm with a range of 0.076mm.

6.3 Measurement of Deflection

The first objective of the research was to build and run an un-bonded laminate die-cast die as a feasibility study for the process. In doing this, the design of this tool would have to allow the second objective to be realised, i.e. the study of deflection on certain laminates in this die, as it would be too expensive to construct two test-dies.

Measuring deflection could be done in two ways, either directly (on-line) or indirectly (off-line). In the case of this thesis, the on-line approach would involve direct observation and measurement of deflection as it occurs during the casting cycle. Off-line experimentation would involve the measurement of deflection, without physically observing the event (this may be through the use of simulation or statistical prediction of what will happen). It also includes making observations, after the event, and deducing what actually happened, during the event, based on the evidence.

6.3.1 Measuring Deflection Directly

Pressure die-casting is an aggressive process. Allsop and Kennedy (1983) state that for large castings (>250×250×250mm) typical velocities for alloy entering the die cavity can reach 125m/sec, with an average of 24 m/sec or 100mph and the pressures exerted on the alloy as it is forced into the die exceeding 200MPa or 2000 kg/cm^2.

One reason why pressure die-casting remains one of the few remaining 'black arts' is the uncertainty of what is actually happening inside the die during casting. Decisions relating to design of gating, runners, venting, fill characteristics etc., are still, almost entirely, achieved through empirical knowledge.

Since the conception of pressure die-casting, researchers have struggled to know the exact flow characteristics in a pressure die-cast die. Most early attempts centred on the use of a thick glass 'window' into the die through which the flow and its effects are recorded (Street, 1977). This process is still used, as it is cheap, but it is fraught with problems. Besides the fact that the glass will shatter after a few castings, the main reason is that glass is a poor thermal conductor compared to die steel and this directly increases the fluidity of the alloy entering the die and therefore alters the way it flows.

Some of the modern approaches used to visualise flow in the die were discussed in the last chapter. The use of x-ray and ultrasonic visualisation has proved very successful in the laboratory but in no way represents a die working in the production environment, and its cost were restrictive within the bounds of this project.

The only option left to directly measure deflection of laminates during casting was to incorporate some form of measurement device on the laminate being observed. The obvious choice was a strain gauge. They are small, discrete and accurate in 'room temperature' experiments but would certainly not work inside a die-cast die. The plastics in which the 'Wheatstone bridge' is encased would melt, as would the solders in the wiring, as would the epoxy resin used to attach it to the laminate. The highest temperature the author could find a stain gauge working at was 500^0C, which was still almost 200^0C lower than the temperature of the aluminium alloy which would be used.

6.3.2 Measuring Deflection Indirectly

If the direct measurement of deflection on the laminates in a test-die were impractical, the question had to be asked whether deflection of 1mm thick H13 sheet could be calculated without resorting to physical observation. Some of the background work which attempts to answer this question can be found in Appendix IV. A small test rig was proposed in which a laminate could be mounted and the effect of deflection and possible ingress simulated. The reason a simulation rig was proposed was to overcome the problems highlighted with direct observation.

A method was explored, through manipulation of conventional elastic displacement equations, by which the whole casting operation could be scaled down with the substitution of molten aluminium for a semi-viscous oil (Appendix IV). The calculations identified a relationship between laminate thickness and fluid pressure which would allow a reduction in the pressure of $^1/_8$th that of a conventional die with each halving of laminate thickness.

The conclusions of this work highlighted further problems which simulation and scaling down of the problem could not overcome. These included the fact that a viscous oil would not behave as molten aluminium alloy and that the loads at work in the die are dynamic, not static, (Szilard 1974) and difficult to scale (Appendix IV).

In the same vein, the potential use of computer simulation to investigate ingress through deflection resulted in an appraisal of the then current Finite Element Modelling (FEM) and Computational Fluid Dynamics (CFD) software. Though thermal analysis within die-casting has been in existence since the mid 1980's, development of commercial CFD packages required to identify alloy flow, viscosity (Navier Stokes) and the stresses imparted on die elements did not start until 1991 (Kim, 1998). By 1996 (when this project began), commercial packages were still awaiting launch. Interestingly, such packages were available in 1998 and were used later in the project for appraisal purposes.

The only option left, with indirect analysis was to measure the effects of deflection after the physical event of the casting cycle was over. The aim, therefore, was to construct a test-die in such a way that if excessive deflection should occur, for a pre-defined laminate protrusion, there would be ingress of molten alloy into the gap. The alloy would either freeze in the gap or be ejected out of the gap, if the laminate sprang back, once the pressure equalised in the die during 3rd phase 'compaction'.

Whatever the up-stand height, should the laminate spring back and eject the molten alloy from the gap (due to its high surface tension and poor wetability), then no 'witness mark' would be visible on the casting around this point, when it was ejected. If, however, ingress did occur and it froze in the gap, then a clear witness mark would have been visible on the underside of the casting. Not only would this indicate at what height/aspect ratio the laminate failed, but the thickness of that witness mark would give a clear indication by what degree deflection occurred.

6.3.3 The Ramp Feature

The objective was, therefore, to design some form of up-stand feature within an un-bonded laminate test-die constructed from laser cut 1mm thick H13 laminates. The feature should present a single laminate as part of a group of laminates, which would receive the force of molten LM24 aluminium alloy, from one direction, as it entered the die cavity. This laminate would deflect in proportion to the height it protrudes above its neighbouring laminates.

To have just a single laminate protruding on it own would give no clear indication of deflection after the event. It will certainly deflect, but in this situation no degree of deflection could be recorded, as no measurable witness mark would be left on the casting. This is demonstrated in Figure 6.2.

As LM24 enters the die cavity from the left it strikes the protruding laminate (green) and deflects it, dependent on its velocity (blue arrow). However, no ingress can occur and, therefore, no witness mark, as its neighbouring laminate (magenta) is fully constrained by the clamping force of the body of the tool.

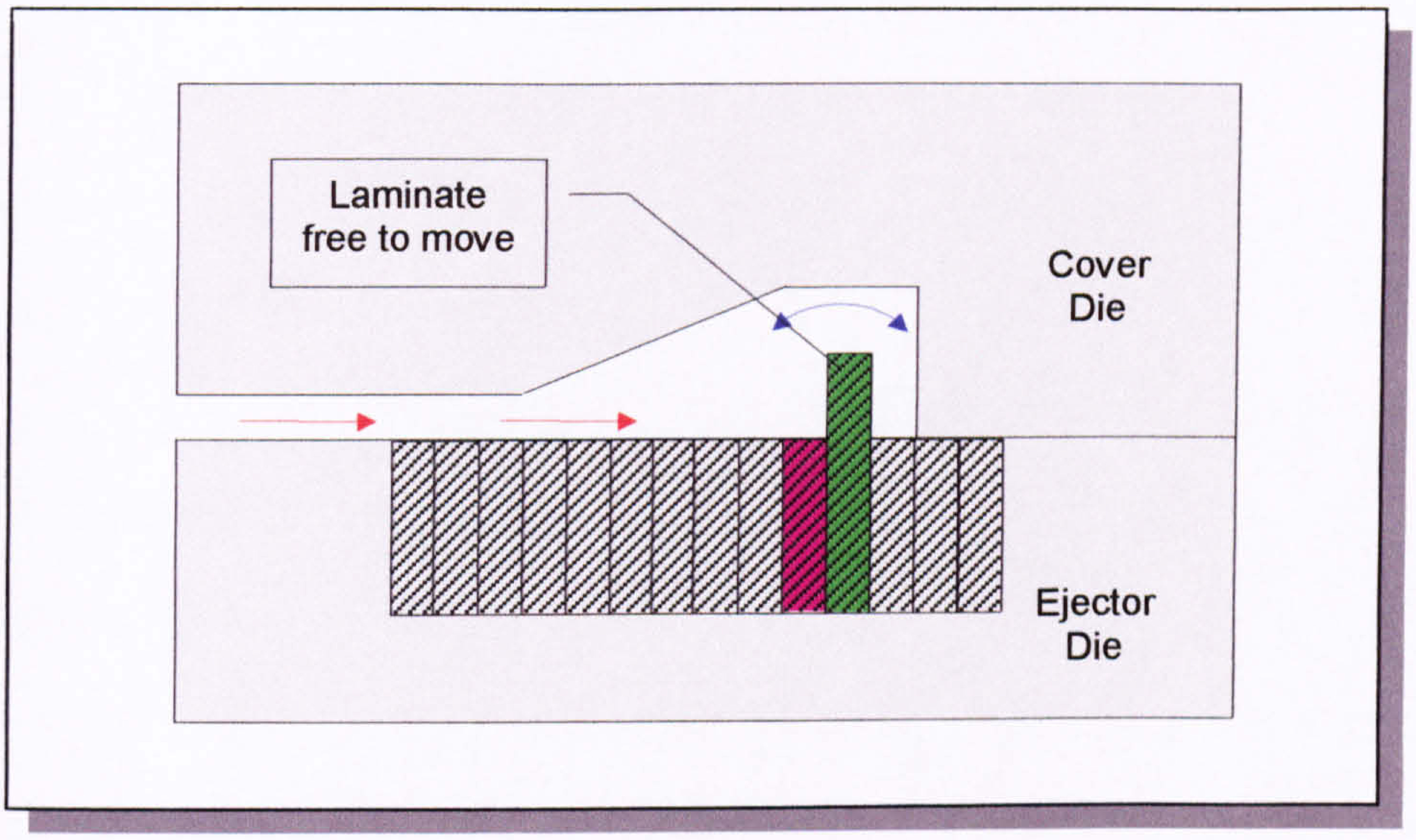


Figure 6.2 The effect of a single protruding laminate

The solution was to design a laminate feature in such a way that the flow of LM24 into the die cavity was deflected upwards off the plane of the parting line as in Figure 6.3.

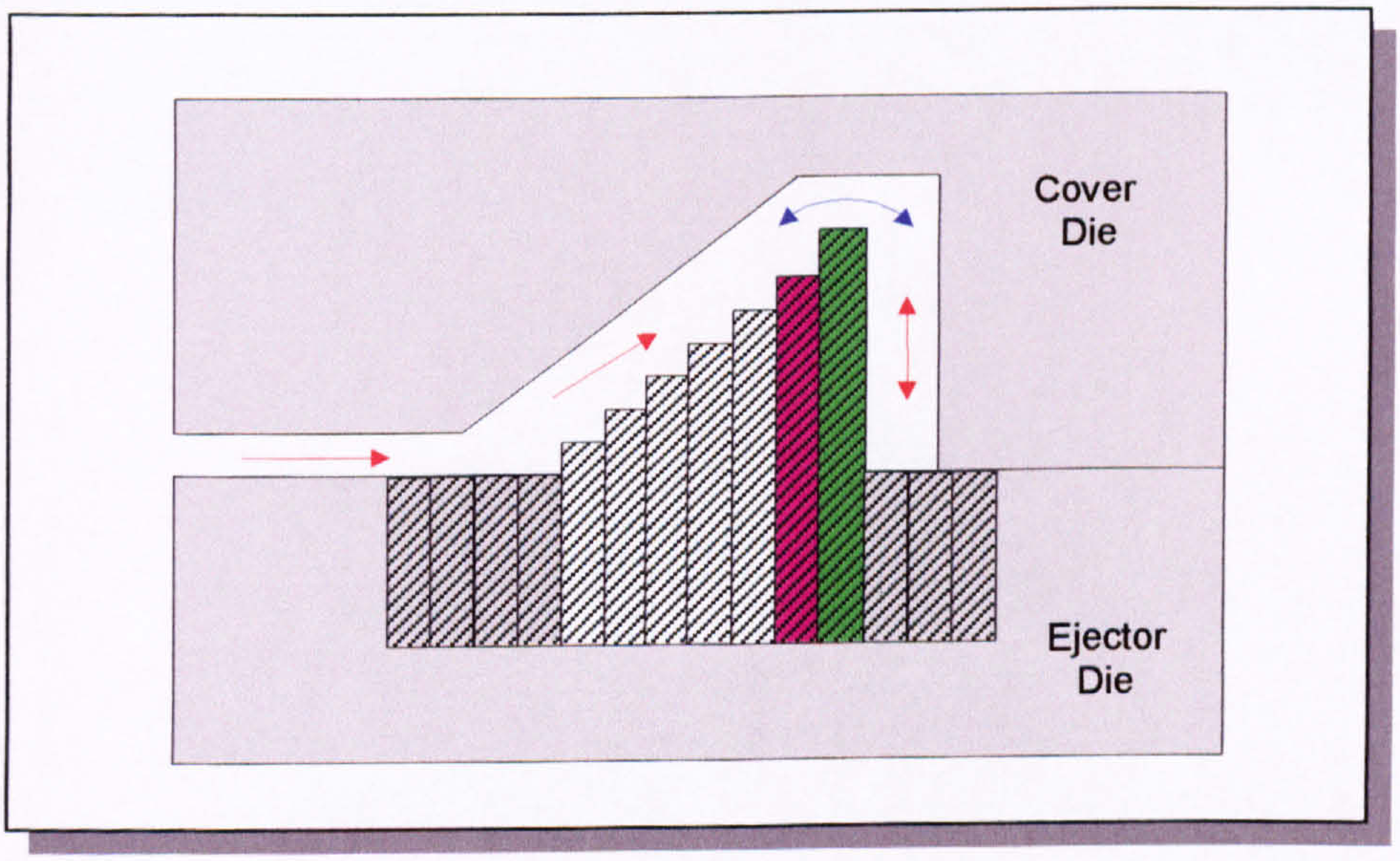


Figure 6.3 The laminate up-stand feature

As molten alloy impinges on the last laminate (green), that laminate will deflect, dependant on its protrusion above its neighbouring laminates in the feature. As it deflects it can freely move away from its neighbour so that ingress, if any, can occur between itself and its neighbour (magenta).

To prevent the entire laminate feature from deflecting and to enhance rigidity in the other laminates in that feature, the angle at which the ramp was set was 45^0 or less. This does imply that the molten LM24 would strike that laminate at an angle (instead of face-on), which would marginally affect the maximum force it could impart on the end laminate. This loss would also be expected to occur in a production laminate die and in no way detracted from the experimental validity of what would happen under normal operating conditions.

6.3.4 The Measurable Witness Mark

Assuming that the casting from the test-die had been cut in cross-section, the view through it would reveal whether ingress had occurred or not. The casting should look similar to the diagram in Figure 6.4.

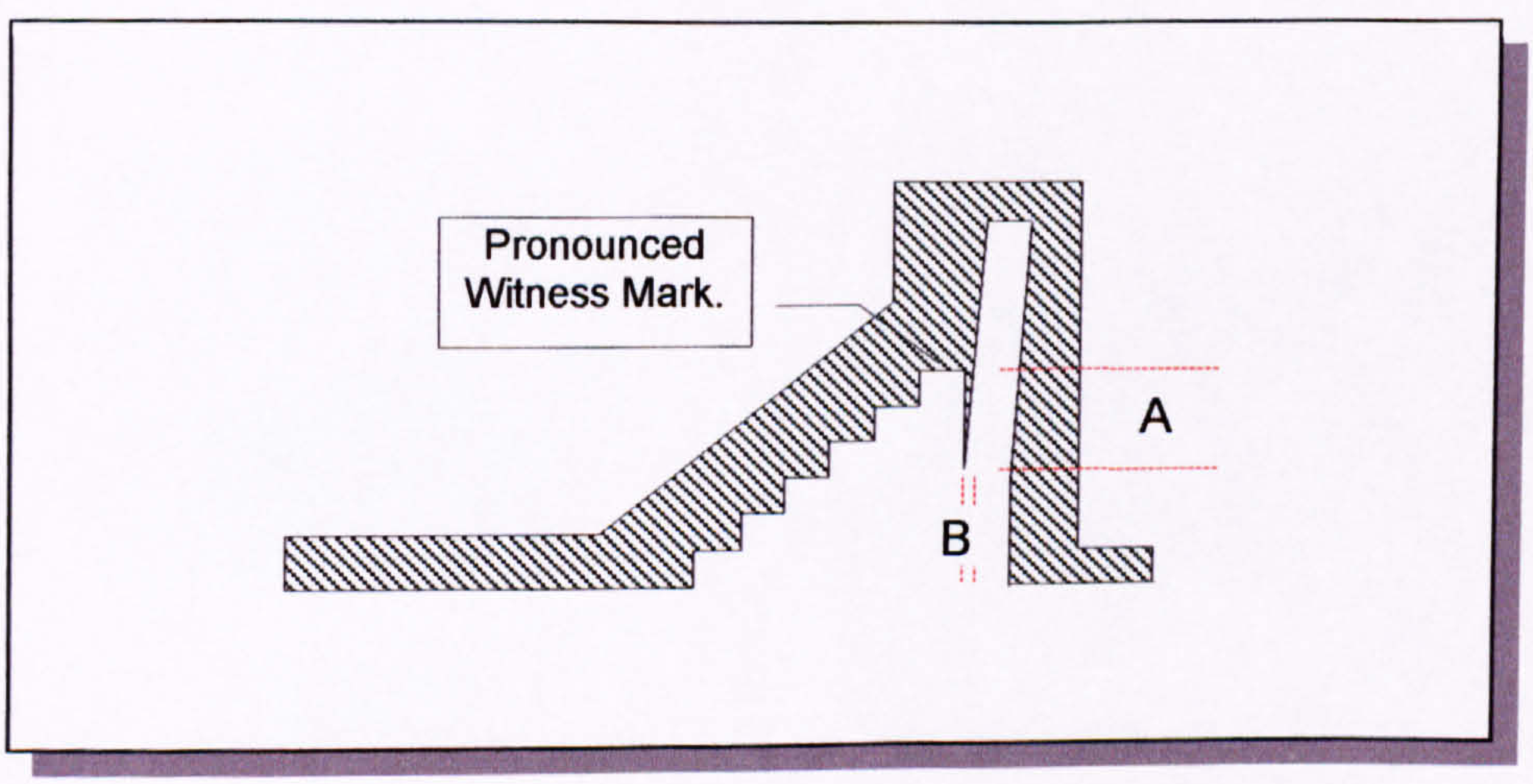


Figure 6.4 Expected view of witness mark on casting

The intention was to measure the witness mark which appeared on the casting. This could be done in two ways, as shown in Figure 6.4, and is depicted by 'A', the penetration of alloy into the gap, or 'B', the width of the witness mark. Only the measurement of the width 'B' would indicate the degree of deflection which occurred. Measuring penetration 'A' could be misleading, as the thin tail formed in the gap between the laminates would narrow off and could easily be snapped off during ejection of the casting giving a false reading.

The simplest way to conduct this experiment would be to use just one ramp feature and adjust the laminate protrusion, by set increments from zero millimetres up to some value dictated by the depth of the die cavity.

This would be impractical, as the die would require complete disassembling between each run. The first test-die, therefore, had an array of laminate ramp features each with a protruding laminate ranging from 0mm to approximately 10mm as shown in Figure 6.5.

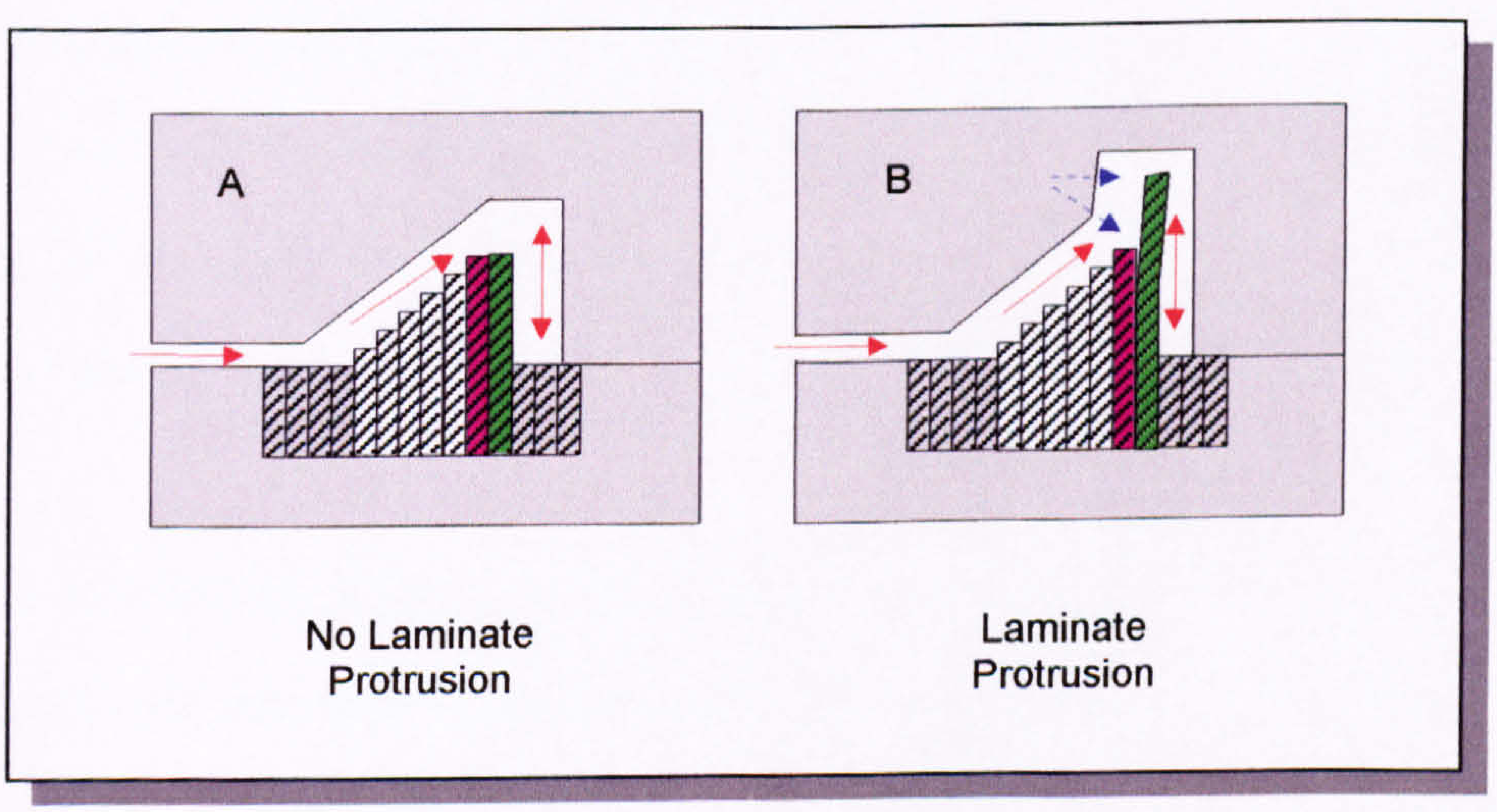


Figure 6.5 Two extremes of laminate protrusion

A protrusion of 10mm should result in enough deflection to cause ingress of molten alloy. Based on bending moments, for a laminate protrusion height and width of 10mm by 10mm above its neighbouring laminate, the maximum force the EMB 100 die-casting machine could impart (66.12 MPa), would be around 6.2 kN (620 kg).

The number of laminate ramp features, which could be placed inside the test-die was dictated by the size of the die which would be used. The primary objective, with Experiment One, was to design and construct a laminate tool for High Pressure Die-casting (HPDC) and assess the tools performance when run on the EMB die-casting machine. By incorporating the laminate ramp features which would be used to measure deflection in the second experiment, it would be possible to verify their design at this stage. During Experiment One, the design of the ramp features proposed for Experiment Two would be monitored for their suitability.

6.4 Design of the Un-bonded Laminate Test-die

For this section, in the report there are numerous schematics for the construction and design of the laminate test-die. Due to the shear quantity and size of these schematics, some will be referred to in the body of the text but will be placed in Appendix V, at the rear of the report.

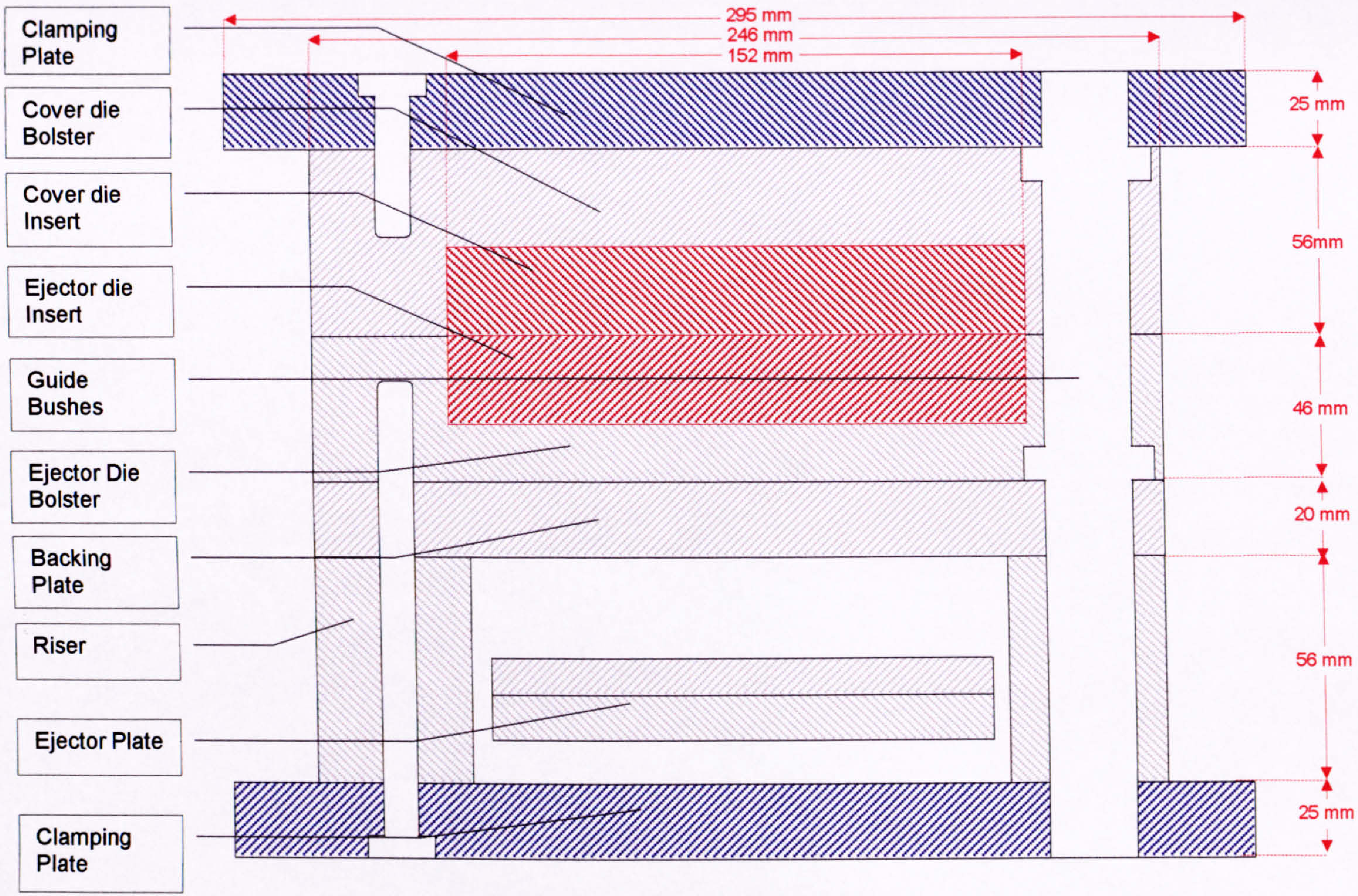
It was decided that, for the construction of the test-die, the cold rolled material would be used, primarily due to its marginally more consistent thickness and better surface finish.

6.4.1 The Die-set

For any die-casting machine, a complete die-set is required. This not only includes the two halves of the die which contain the detail of the casting but also additional die-plates which bolt to the rear of the cover and ejector die and enable the assembly to be clamped securely to the fixed and moving platens.

In addition, there is space within the die-set for the installation of an ejector plate. Attached to the plate are the individual ejector rods which run through the ejector die and into the die cavity, so that the part can be pushed off any up-stand detail which the casting may shrink onto. The space for the ejector plate is created through the use of two riser plates which are simple two narrow sections of steel which sit either side of the ejector plate. The die-set, with its various elements, is shown in Figure 6.6.

Die-sets for HPDC generally fall into two categories. The first, are dies whose detail is machined into the surface of a solid piece of steel. The second is to machine the ejector and cover die detail onto smaller blocks of steel and fix them, as inserts, into a solid metal bolster. The latter approach is often used so that different cavity inserts can be quickly inserted into a standard bolster, this reduces the time taken to change a tool on a die-casting machine. The concept of laminate tooling is one of flexibility with the ability to make design changes to form a new tool. It is simpler if the laminate tool is an insert, clamped into a solid metal bolster which can be removed at a later date without affecting the rest of the die-set.



TITLE: Schematic of Die Set Showing Location of Laminated Die Insert.

DO NOT SCALE

Dwg No: One

Scale: N/A

Date: 11-04-97

Material: Die – H13 Set - N2

Finish: N/A

Heat treatment: N/A

NAME: Rupert Soar

Figure 6.6 Details of die-set and laminate insert

Revision no:

Another factor in the decision to use bolsters and laminate inserts, was that in the corners of the die-set are the 'guide bushes' which are, essentially, a large peg and hole to ensure that the two halves of the die come together accurately. These bushes take a lot of force, over time, and need to be constrained in solid metal. Laminates would not be robust enough to stop them from moving slightly.

From the dimensions of the fixed and moveable platens in the EMB 100 machine and the distance between the tie bars, the maximum dimensions for the test-die was 246×295mm. If the bolster and die-set were any larger it would be impossible to manoeuvre the die-set in and out of the machine. A schematic of the die-set, in place, between the two platens is shown in Appendix V(Figure 1).

The shot sleeve is also shown in position, to demonstrate how the LM24 will enter the die. The injection plunger extends to the end of the shot sleeve during each shot. The end of the shot sleeve, to the point at which the alloy travel through 90^0 into the inlet gate, is tapered slightly to ensure the casting's easy removal when the dies open. The ejector plate is visible, but not the rods which extend into the die or the ejector bar which extends backwards through the moving platen to a stationary plate, which pushes the ejectors forward as the moving platen moves backwards to remove the casting.

6.4.2 Design of the Laminate Inserts

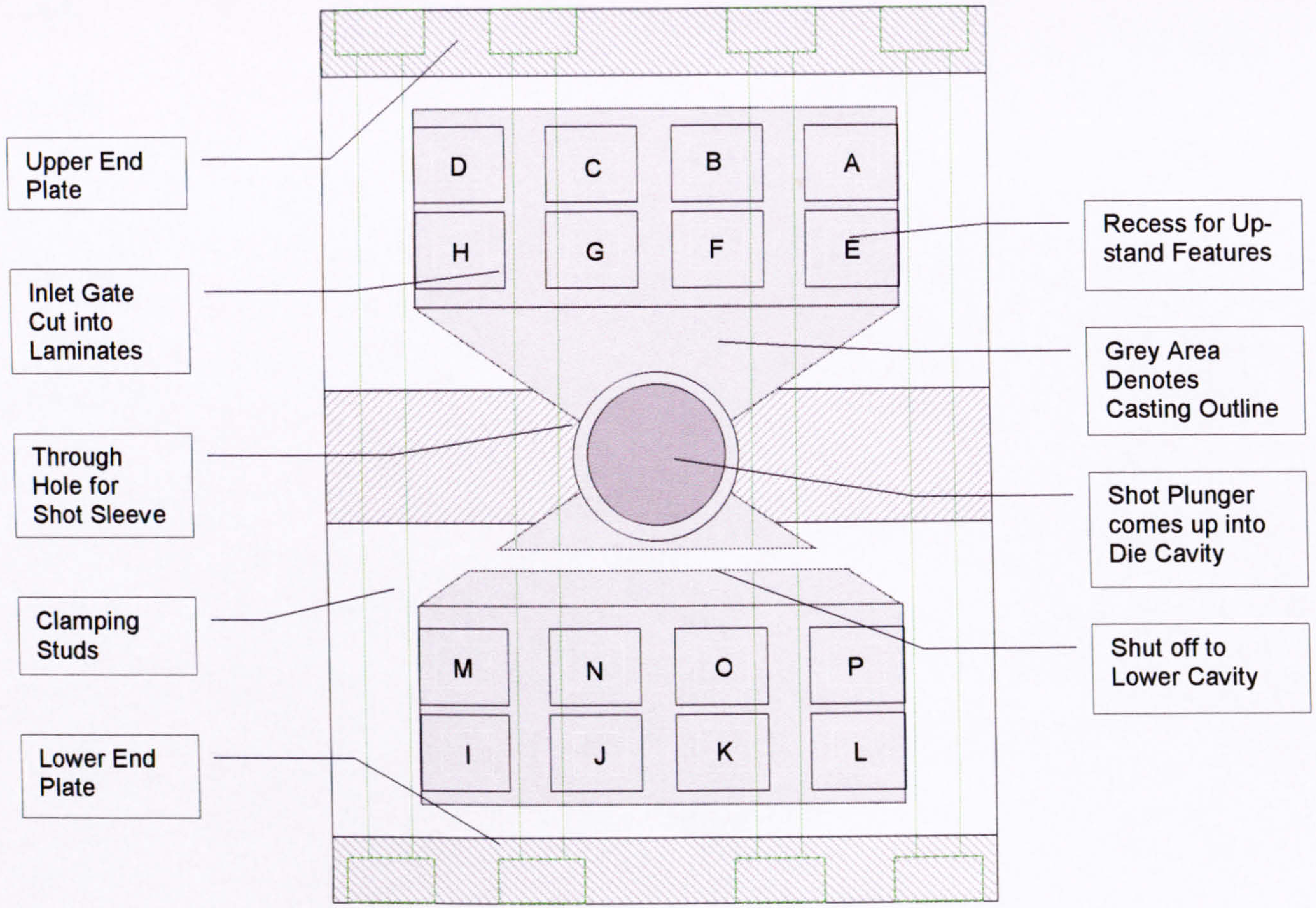
The design of the laminate inserts were dictated by the following constraints:

- The laminates must be orientated so that the ramp features discussed previously could be incorporated.

- There should be as many ramp features as possible within the allotted space for the cavity.
- LM24 entering the die cavity must strike the laminate protrusions of each ramp feature face on.
- The flow of LM24 passing into the die cavity must be laminar and travelling in a straight line towards the rear of the die.
- The laminates must be replaceable for closer analysis of deflection during Experiment Two.

Various iterations were considered for the design of the laminate inserts and the design which was ultimately settled on incorporated an array of eight ramp features in the upper and lower halves of the die. In each array, of eight up-stand features, there was a laminate which protruded from the rear of the ramp feature. Each protrusion increased in height above the ramp feature, starting at 0mm, 0.5mm, 1mm, 2mm, 3mm, 4mm, 5mm and 6mm. The same incremental increases in height were duplicated in the second array of eight up-stands in the lower half of the die.

Plan views of the laminate cover die inserts are shown in Figures 6.7 with further detail in Appendix V (Figure 2), the laminate ejector die in Figure 6.8 with further detail in Appendix V (Figure 3), and a cross-sectional view in Figure 6.9.



TITLE:

Laminate Test Die . Plan View of Cover Die.

DO NOT SCALE

Dwg No: Three

Scale: 1:1.6

Material: 1mm thick H13

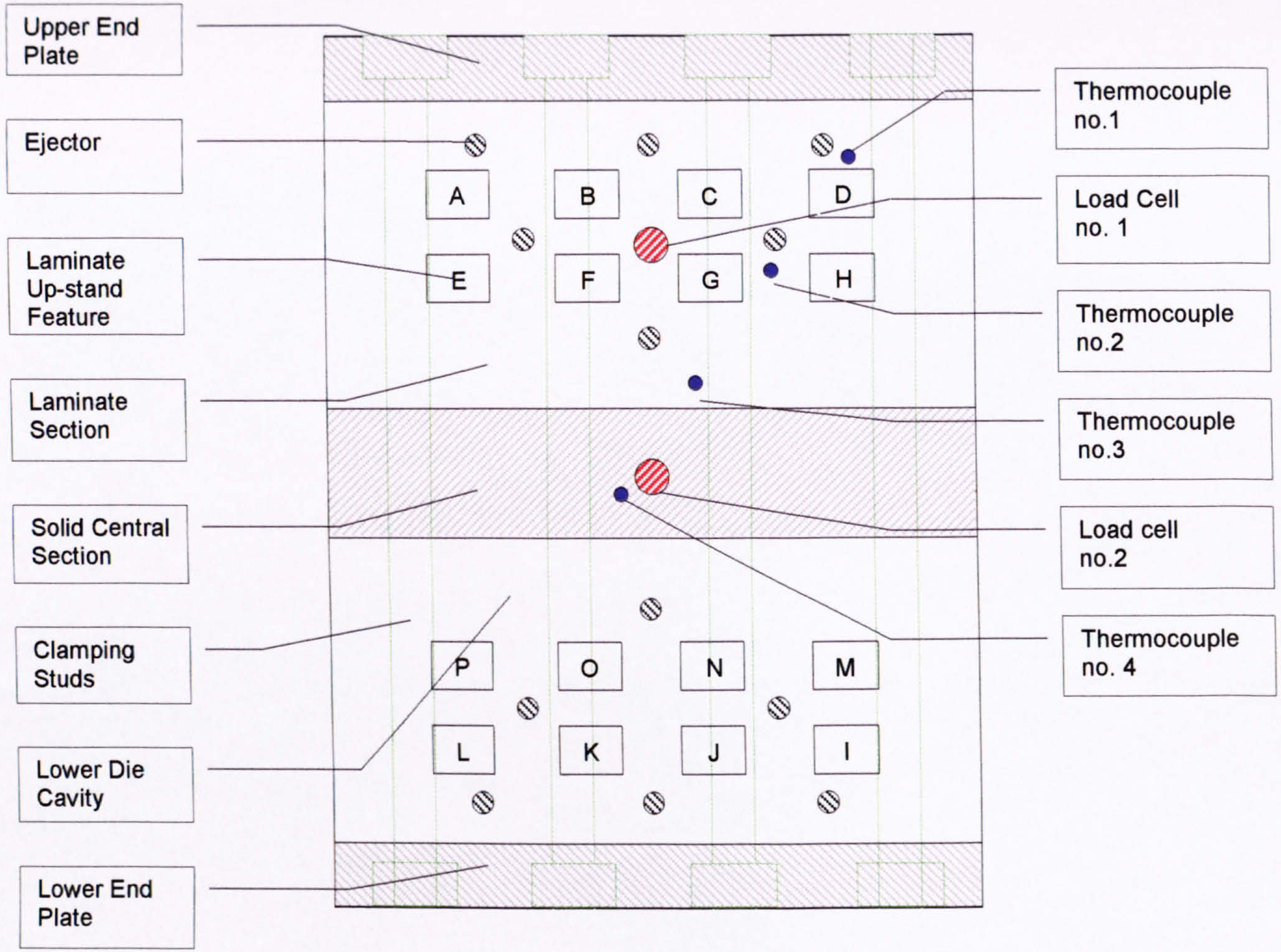
Finish: As Rolled

Heat treatment: Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 6.7 Plan view of laminate cover die insert

Revision no:

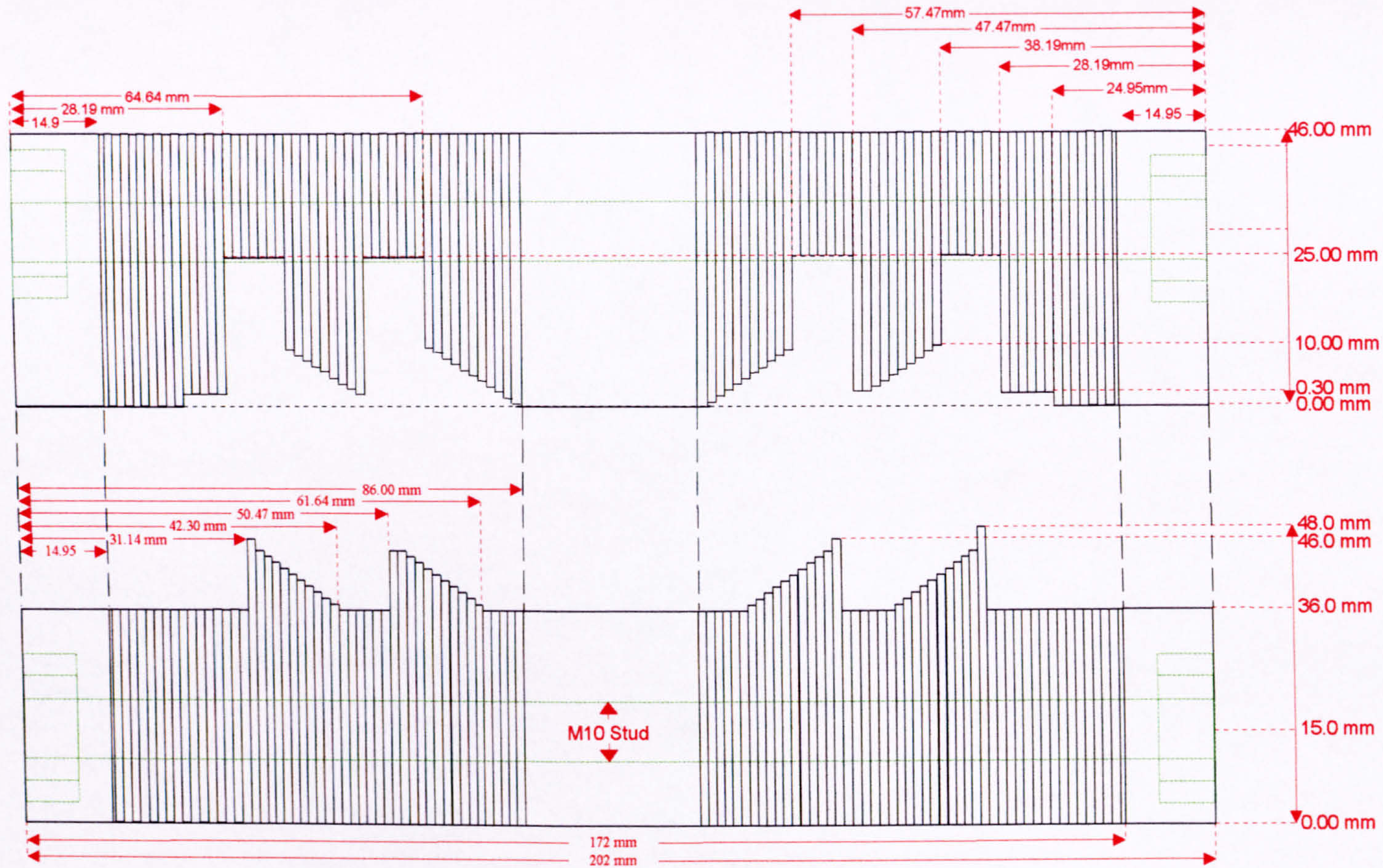


TITLE:	Laminate Test Die . Plan View of Ejector Die.
DO NOT SCALE	
Dwg No:	Five
Scale:	1:1.6
Date:	25-07-97
Material:	1mm thick H13
Finish:	As Rolled
Heat treatment:	Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 6.8 Plan view of laminate ejector die insert

Revision no:



TITLE:

Cross sectional View AA of the Laminate Insert Test Piece.

DO NOT SCALE

Dwg No: Seven

Scale: 1:1.2

Date: 25-07-97

Material: 1mm thick H13

Finish: As Rolled

Heat treatment: Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 6.9 Cross-sectional view of laminate inserts

Revision no:

From the cross-sectional view in Figure 6.9 it can be seen that the laminates are orientated vertically (or perpendicular) to the parting line. This orientation gives the most detail with the firmest support for any up-stand feature, by the clamping of every plate within the main body of the tool. The laminate test-die uses an end plate for both halves of the laminate inserts. These are machined from solid H13 stock and, at 15mm thick, they provide adequate clamping force to the laminates prior to insertion into the bolsters and spread the load of the studs which run through the length of the two inserts. This ensures that the laminates remain square to the tool and to each other. Details are shown in Appendix V(Figure 4).

In addition to the end-plates, there is the inclusion of a solid central section to the tool. The reason for the solid central section was felt prudent, as it is through this part of the tool that alloy will enter the die cavity through the channel visible in Figures 6.7. This area must be rigid, on both ejector and cover side, as there is some interaction with the injection plunger on the cover die. This is also the point at which the molten alloy's direction changes through 90^0, as it strikes the central section on the ejector side, before entering the inlet gate to the upper die cavity.

The next point to clarify is the use of two die cavities, or two sets of eight identical up-stand arrays. In the cold chamber die-casting process, the die cavity always sits above the level of the shot sleeve. If it sits below this level, alloy will flow down into the die cavity as soon as alloy is placed in the shot sleeve.

To ensure that the die would sit centrally to the platens would require a large amount of dead space in the lower part of the die. Instead of leaving this part of the die empty, it was realised that if the die cavity in the upper half were mirrored in the lower half then twice as many runs of a tool could be conducted. Each run would have to end if a laminate failed prematurely. If the ejector die could be rotated through 180^0 then a completely new set of laminates could be located in the upper half of the die and a run continued without having to strip the die.

Ejectors are visible on the schematics for the ejector die and are distributed evenly throughout the die cavity to ensure that the casting can be removed from the die with minimal distortion. To ensure that the casting could withstand deflection during ejection, the casting thickness was set at 3mm over its entire area. To have it any thinner presented the risk of the 5mm diameter ejector rods pushing through the casting during ejection.

6.4.3 Design of the Inlet Gate

The primary objective for the inlet gate, used in the laminate test die, was to spread the flow of the alloy coming from the shot sleeve into the die chamber. This flow had to be spread evenly over the width of the eight up-stand arrays in the upper die cavity and ensure that, as the alloy flowed into the die, it progressed evenly up the length of the die cavity before striking the rear wall.

This flow must be laminar. To ensure this, one simple rule had to be adhered to. The inlet gate began with a cross-sectional area dictated by the opening created by the shot sleeve. In the example of the laminated test die, the inlet must widened along its length to spread the flow of incoming alloy so that the alloy was flowing in a straight line toward the first set of four laminate ramp features. This spreading of the flow must be achieved without changing the cross-sectional area of the inlet gate along its length as shown in Appendix V (Figure 5).

If the cross-sectional area of the inlet gate is reduced, the speed of the flow through the gate increases dramatically and will spray the alloy into the die, as droplets. If the cross-sectional area of the gate is increased, the gate will no longer influence the spread of the alloy going through it and the alloy will take the line of least resistance and not spread at the final exit point of the gate. If the cross-sectional area should increase and then decrease along the gate's length, before the alloy exits the gate, then a large pressure drop occurs in the alloy as it passes through the gate. This disrupts the flow and any entrained gasses in the molten alloy will appear as bubbles, which affect the laminar flow and material properties.

During normal die-cast die design there will rarely be one inlet gate, as it is difficult to ensure that the flow remains constant and laminar. The designer will normally split the flow of molten alloy down various runners which take the alloy to different points around the die cavity to be filled. This could not be done in this experiment as the effects of deflection had to be observed in one direction, as all the laminates are aligned in the same plane.

6.4.4 Measurement of Temperature within the Die

The age of the EMB 100 die-casting machine was of some concern. At the outset of this work, the machine had to undergo extensive re-work and servicing (it's last recorded service was 1976). Most of the pneumatic valves had seized and required replacement and there were problems with the pressurised air reservoir necessary to run the machine. Making matters worse was the lack of any efficient pressure regulation and temperature control within the machine, as is common on modern machines. Modern machines will constantly calculate shot profiles in real time and monitor die heating and cooling, whereas, at the time the EMB was built, the control of the quality of the casting was largely down to an operator's skill.

If the EMB was going to be used for experimentation, then there would have to be the inclusion of temperature monitoring within the test-die as well as pressure monitoring during each shot. The average temperature for the die in die-casting should be between 175-200^{0}C. As each shot goes into the die, it will begin to raise the dies average temperature. During full-scale production, the temperature in the die would be held constant through the use of cooling pipes built into the die. This was not an option for the laminate test-die, as the intention was to leave the laminates un-bonded, and there was too great a risk that running conformal cooling channels through the laminate die would result in water leaking between the laminates into the die cavity. The most effective method to control the test-die temperature was to incorporate temperature probes, as close to the die surface as possible, and after each shot wait until the probes indicated that the die temperature had fallen to within 175-200^{0}C.

Four K-type thermo-couples were incorporated into the design and their location is represented by the blue dots, shown previously, in Figure 6.8. Thermo-couples require no excitation as they generate their own voltage between two disparate metals at the tip of the device as the temperature changes. K-type thermo-couples generate voltage of about 40μV for every degree Celsius change. The spacing between the four thermocouples was kept equidistant, so that it would be possible to look at temperature gradients across the die surface. With pressure die-casting, it is essential to bring the die up to its casting temperature before the run begins. If the die is too cool, the alloy may freeze before the die cavity is filled, which can damage narrow up-stand detail in the die if 3rd phase compaction should engage prematurely. Likewise, if the die is too hot, the alloy will not freeze sufficiently, prior to ejection, and the ejector pins will be forced through the casting.

Proprietary hardware and software, from Pico Technologies Ltd, was used to record the data from the four thermocouples. The thermo-couples fed into an analogue to digital converter which amplified the signal before converting it, prior to transmission to the I/O serial port, to a standard IBM compatible PC. Sampling rates, up to one reading every 800ms for all four channels, was possible. The system included a low pass filter to reduce any interference from surrounding equipment which could be adjusted to improve response times. The software was DOS based and allowed various types of run to be initiated. For this experiment, the system was triggered manually at the start of each run. The system could scale the data, if needed, and report the results as a plotted graph as a temperature change against time.

K-type thermocouples have a sensitivity range from -270^{0}C to 1370^{0}C, though their performance will decline through extended use at high temperatures. This situation was not expected, due to the comparatively low temperatures, which would be experienced during the trials. Blind holes were drilled through the rear of the laminate inserts into which the thermocouples were sealed. To ensure that an efficient transfer of heat took place between the die and the tips of the thermocouples, a high temperature conductive paste was used to fill the blind holes. The software would monitor the temperature on the die surface at all times and would record any temperature change as the shot was initiated for later appraisal.

6.4.5 Measurement of Pressure within the die

With uncertain pneumatic control on the EMB machine, it was essential to include some form of pressure monitoring within the die cavity. If the pressure exerted on the molten alloy by the pneumatics changed, between shots, so would the velocity of the alloy as it travelled through the die and this would directly affect the deflection results in Experiment Two.

Essentially, one load cell would suffice, placed strategically in the die cavity. This cell would indicate any variation in pressure between the shots. However, it was decided to incorporate two load cells (there was no room for three) placed at different positions in the die. A strain gauge attached to an individual laminate was out of the question due to the heat present. Therefore, a method was devised whereby the pressure in the die would be transferred away from the die cavity using a false ejector pin (load cells could not be attached directly to the ejectors as they would be crushed during ejection).

The high pressures in pressure die-casting severely limited the type of load cell, which could be used. The maximum load the EMB could exert on each 5mm diameter ejector pin was 66.12MPa. Dividing this by the cross-sectional area of each pin gave 125Kgs load on each cell. Space restrictions in the die, due to ejectors and thermocouple arrays, meant that two different types of load cell had to be used as shown in Figure 6.10.

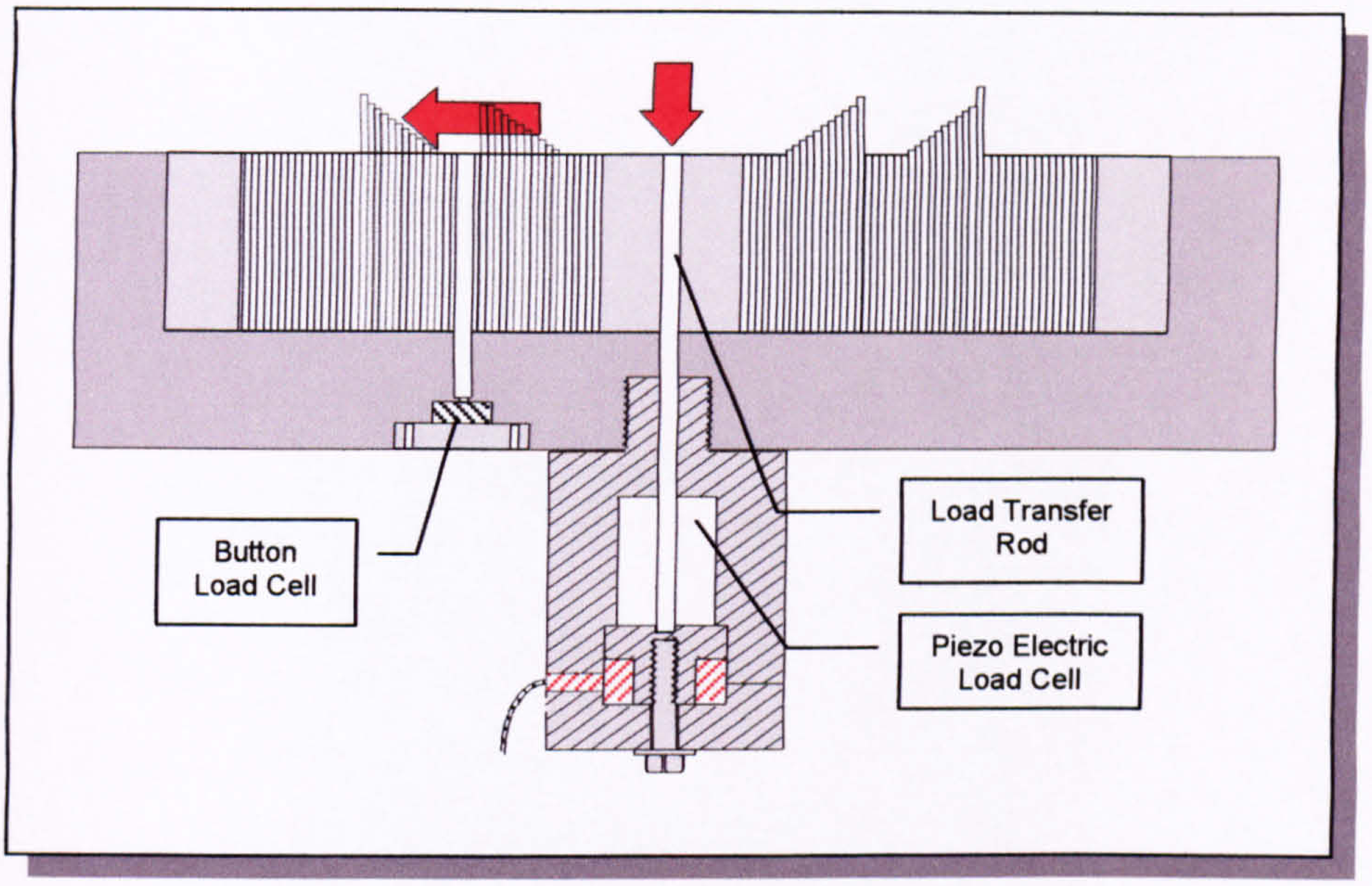


Figure 6.10 Schematic of installation of load cells into test-die

The primary position to measure pressure in the EMB's pneumatic system was in the centre of the die. This position is where the alloy first enters the die, before passing through the inlet gate. This point is also where the plunger will compact the freezing alloy most during the 3rd phase and would, therefore, give a clear reading of the pressure in the pneumatic system on each shot.

This particular location for the load cell, in the test-die, had adequate room and minimum obstruction which allowed the design and construction of a housing for a piezo-electric load cell, located away from the die surface, to reduce the affects of heat on the cell. The load cell was manufactured by Kistler and is the 'washer' design (type 9061A). Specifications for the load cell are shown in Table 6.6.

Manufacturer	Kistler
Type	9061A
Range kN	0-200
Overload kN	250
Sensitivity pC/N	~ -4.3
Threshold N	0.01
Bending moment Nm	830
Rigidity kN/µm	~14
Temperature Range ^{0}C	-196 – 250
Capacitance pF	~148
Dimensions mm	D 52.5 - H 15
Linearity %FSO	≤ ± 1
Hysteresis %FSO	< 0.5
Temperature Sensitivity %/^{0}C	-0.02

Table 6.6 Specifications for Kistler load cell

The housing had to be robust to ensure accurate measurement and is shown in detail in Appendix V (Figures 6 and 7).

The second load cell in the design was offset and located deep within the die cavity to measure the pressures during 3rd phase 'compaction'. Theoretically, the pressures would be similar to that of the primary load cell but this may not be the case, in reality, as the alloy has passed through the inlet gate and partial solidification would have occurred before 3rd phase was initiated and, therefore, the pressures exerted in the die cavity would be significantly less.

Space was at a premium in this location and a large housing would obstruct the ejectors and thermo-couples in the die. An alternative type of load cell had to be found with dimensions no wider than 10mm or thicker than 7mm. A search revealed DS Europe in

Italy which produces a button load cell (BC302 with Wheatstone Bridge) within the dimensions. The specification are shown in Table 6.7:

Manufacturer	DS Europe SRL.
Type	BC 302
Measuring Range Kg FS	60-100
Sensitivity mV/V FS typical	2.0
Repeatability Error % FS	≤ ± 0.1
Total Error % FS	≤ ± 0.5
Zero Unbalance % FS	≤ ± 3
Thermal Shift of Zero of Sensitivity % FS/^{0}C	≤ ± 0.08
Excitation Vdc/ac	5
Overload FS max.	1.5

Table 6.7 Specifications for Button load cell

Maximum loading on this type of cell was 100kg with a 50kg safety margin. As the loads exerted within the die should be less than those exerted on the piezo-electric load cell, this range was deemed satisfactory (this is the highest specification for button load cells).

Data acquisition from the button load cell was by ±5 volts excitation across the bridge. Under maximum deflection, this gives a 10mV output which was amplified to within 0-5 volts for the DAS58 (Omega Electronics) data acquisition board. Calibration was done using 2Kg weights to check linearity which proved effective up to 10Kg but the readings had a tendency to drift from zero with any temperature increase. The device is rated to 100^{0}C but, through consultation with the manufacturer, this can be increased to as much as 200^{0}C in practice. For these experiments, the preheated die temperature would be around 175^{0}C–200^{0}C which meant that the button cells had to be zeroed once the die was up to casting temperature.

DAS58 is a flexible data-logging package, it can sample a maximum of one million samples in a second. Using more than one channel means dividing up the sampling rate appropriately. For this experiment, one thousand samples per second was more than adequate for two channels over ten seconds. DAS58 records the output voltage in mV. A 10Kg load gave 295mV output and 100Kgs gave 3volts. This was a suitable range for DAS58 which works between 0-5 volts.

The Kistler load cell required no excitation as it is a piezo electric pressure transducer. The uniqueness of these devices is their accuracy over a great range, excellent linearity and the ability to reset the zero as and when it fluctuates between measurements.

This last facility would prove invaluable as the design of the load cell carrier was such that, as the tool heated up, it would place a greater load on the load cell. Without the zeroing capability it would have been impossible to compensate for this heat and expansion.

Calibration was done using a calibrated hydraulic press. As the cell is loaded, an electric pulse emitted from the cell is measure via a charge amplifier. The charge amplifier was a Kistler type 5007. Under different loading conditions, pulses emitted from the transducer are proportional to the loads applied so there is a scaling function on the charge amplifier to compensate for readings in the grams, kilograms or tonnes. For this experiment, the scaling was set to 5000 mechanical units recorded for every volt emitted to the DAS58 data logging software. Volts emitted from the charge amplifier were recorded on a voltmeter and then on DAS58, so that linearity could be checked as well as any error between the meter and the DAS58 data-logger.

This data is shown Table 6.8 for three, pre-set, loads of 1 kN, 2 kN and 3 kN. Prior calculations had shown that the maximum load exerted by the EMB machine on the molten material, as it entered the die, would not exceed 3 Kn.

Load (kN)	Millivolts (Meter)	Millivolts (DAS58)
1kN	1370	1107
2kN	2790	2230
3kN	4260	3456

Table 6.8 Pre-set loads for Kistler load cell

There was a difference between the readings measured by the voltmeter and the DAS58 software. The voltmeter was pre-calibrated and correct and the difference in the reading between the two were used to calculate the error in the DAS58 software to compensate for it during the experiments.

To confirm linearity, a separate test was done so that compensation could be made for the error in the DAS58 software. During this test 100,000 data points were collected. A graph was generated and is shown in Figure 6.11 and shows excellent linearity:

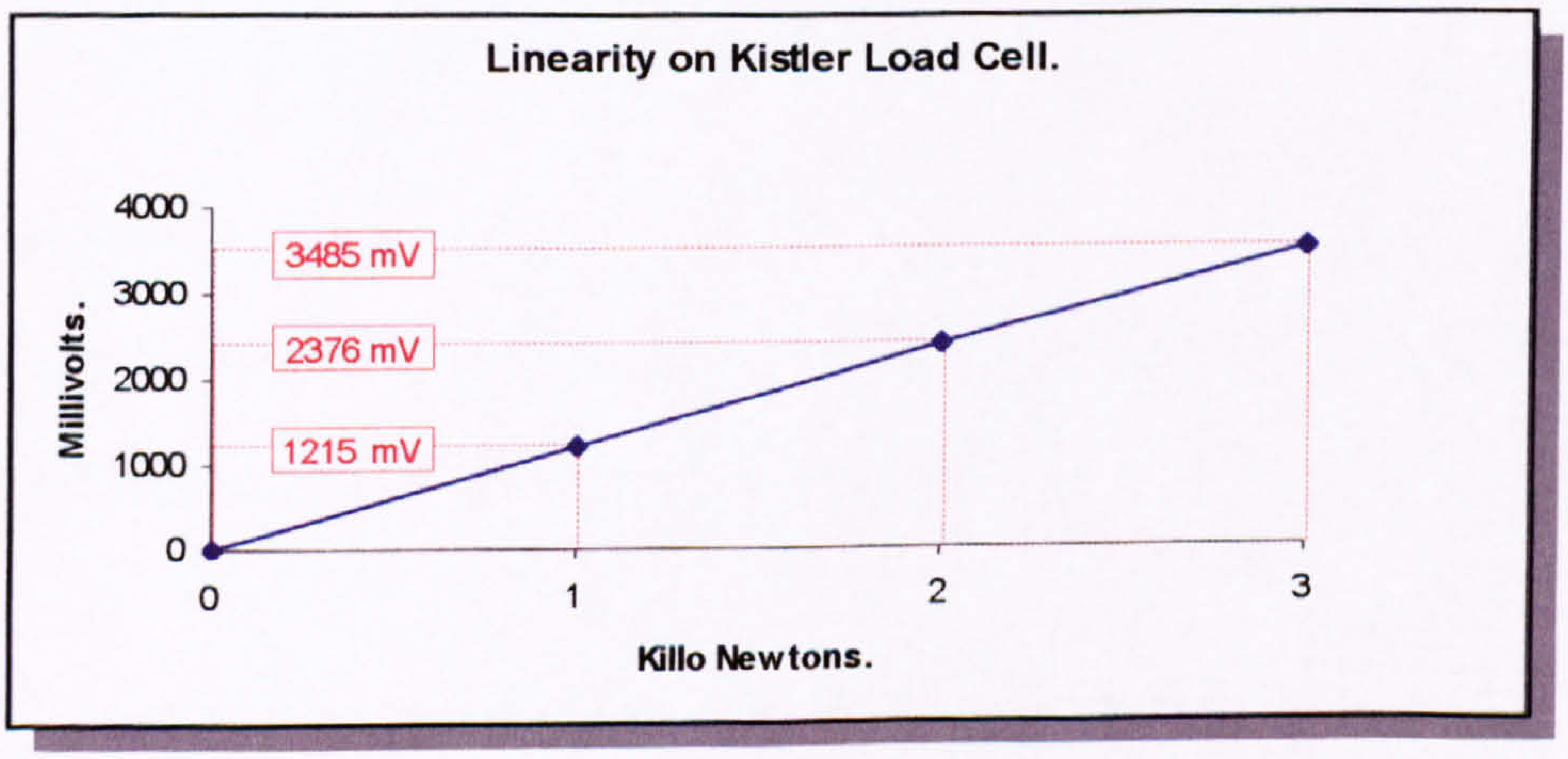


Figure 6.11 Linearity test for Kistler load cell

As stated before, this type of cell could be zeroed at any point. In practice it was inadvisable to measure small loads with the piezo-cell fully relaxed (i.e. under no pre-load). For accurate measurement of small loads, the cell must be pre-tensioned prior to the experiment starting. This was the function of the tensioning bolt shown in Appendix V (Figure 6.7) at the top of the housing. A pre-load of 10 kN was applied to the cell before the each experiment was begun. The design also allowed this pre-tension to be adjusted during the experiments to compensate for any expansion through a temperature rise.

6.5 Construction and Assembly of the Laminate Test-die

Many of the issues relating to the production of a laminate tool have been covered in Chapter 4. Designing and producing a laminate tool for HPDC presented its own set of unique problems.

6.5.1 Definition of the CAD Model

The process of Laminate Tooling begins with the definition of a 3D Solid CAD model. In this case the software package was EDS Unigraphics running on a Silicon Graphics O_2, Unix platform. The model is reproduced in Figure 6.12.

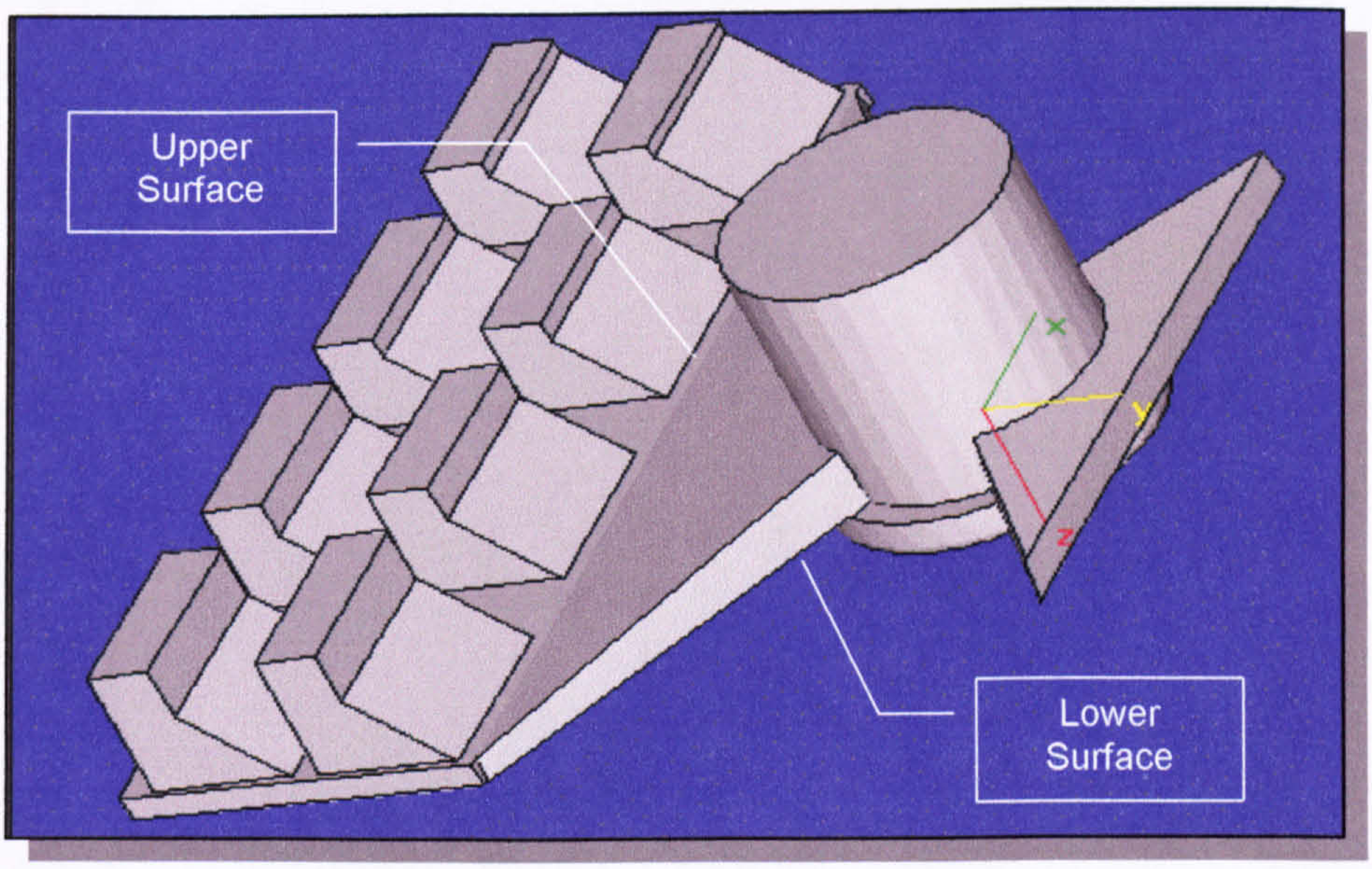


Figure 6.12 3D CAD model of the casting from the laminate test-die

The upper and lower surfaces of this model were separated and the upper surface used to define the cover die and the lower surface, the ejector die. In the case of the test-die, the model was mirrored to produce two sets of casting impressions on both cover and ejector die as shown below in Figure 6.13 and 6.14.

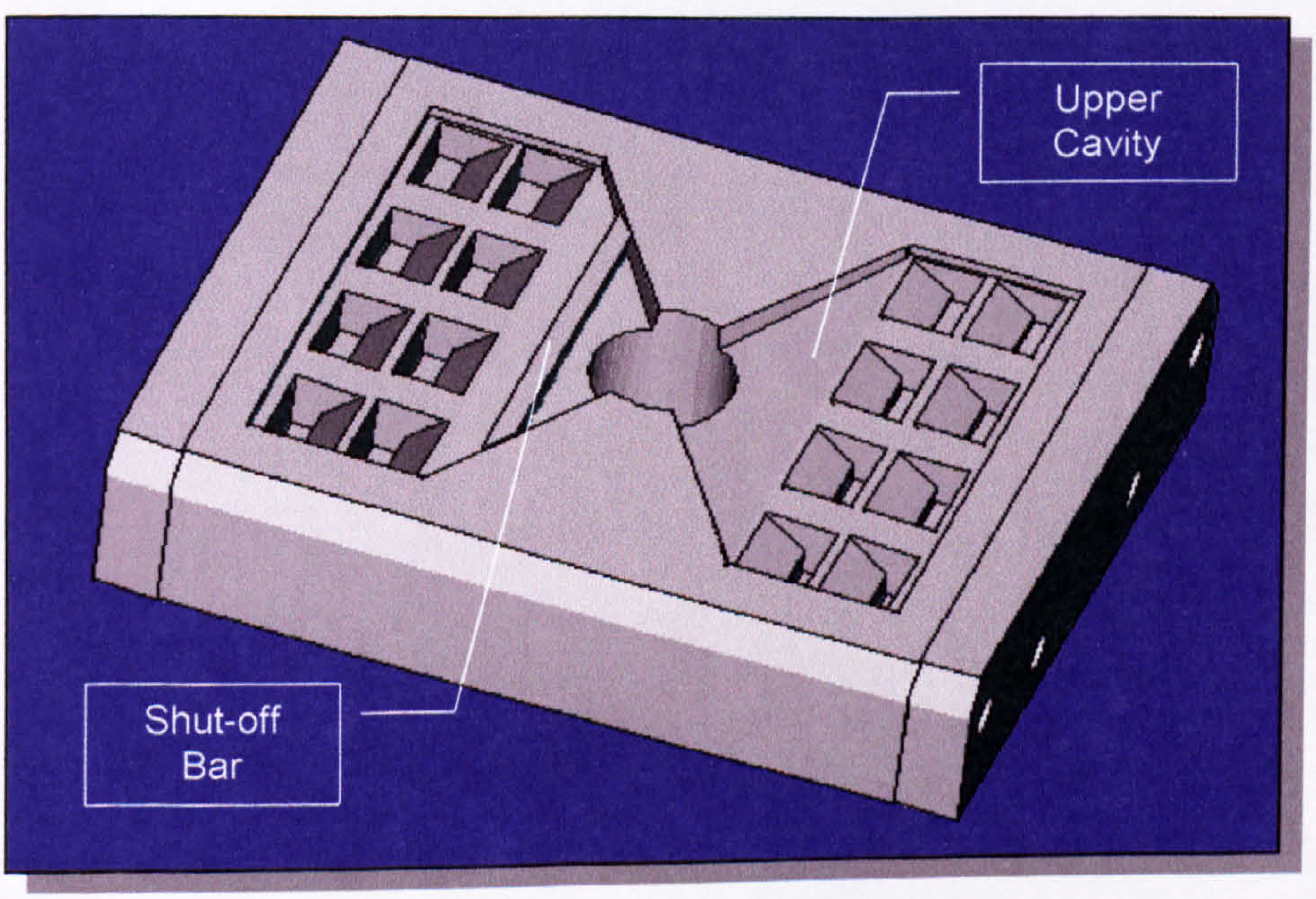


Figure 6.13 3D CAD model of cover die with clamping plates

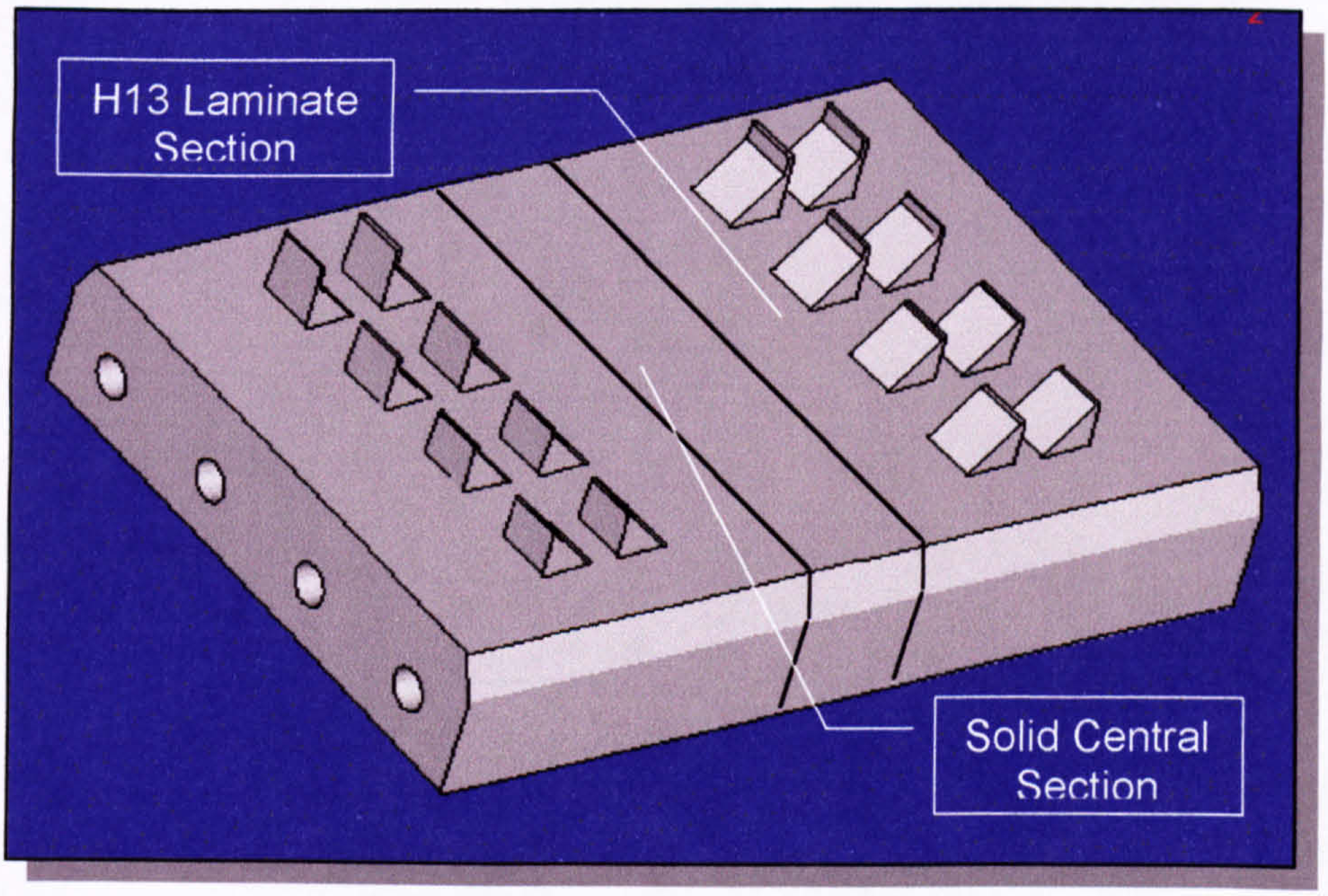


Figure 6.14 3D CAD model of ejector die showing solid central section

6.5.2 Slicing and Cutting the Profiles

The model could then be sliced using an off-set slicing sub-routine, developed for this purpose (current STL slicing operations are just as applicable), in which the offset for each slice was dictated by the mean thickness of the cold rolled H13 tool steel sheet (1.045mm). Each slice was exported as Direct Exchange Format (.DXF) to the laser profiling software where each slice was laid over a CAD representation of each sheet of steel to be used. Each slice was automatically 'nested' to ensure minimum wastage of material. The laminates were cut and tumble finished as previously discussed.

6.5.3 Assembling the Laminate Tool

With the laminates ready for assembly, the central solid section and end-plates were machined from solid H13 stock and the laminates and plates clamped together to ensure that both halves of the tool aligned. It is possible that if the mean thickness deviates from the actual thickness of the cut laminates the tool can be adjusted by adding, or removing, laminates. The clamped cover die is shown in Figure 6.15 prior to finishing.

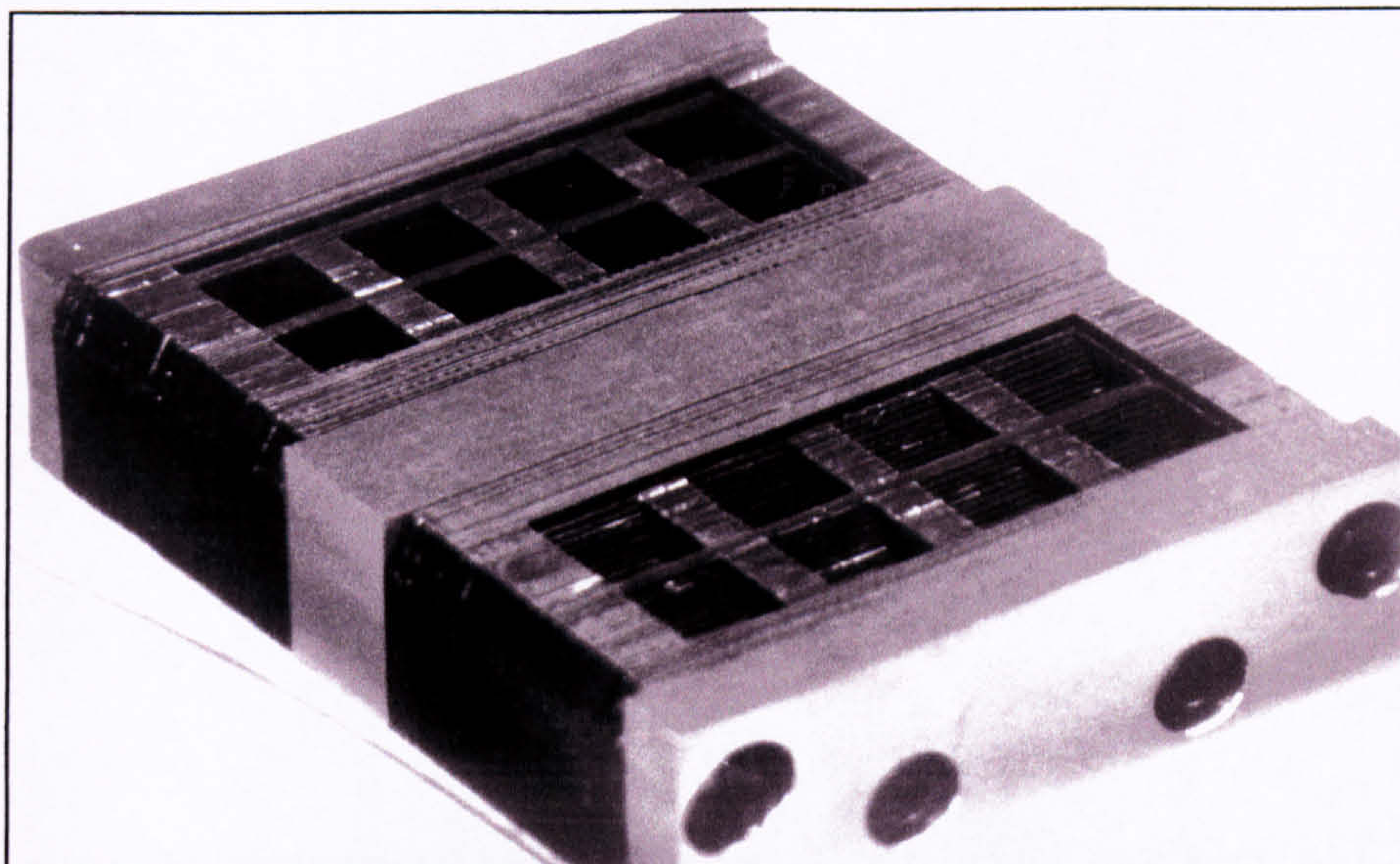


Figure 6.15 Clamped laminates for the cover die

The laminate inserts were then machined and ground over the parting plane to ensure that both halves of the tool would meet with no gaps for molten LM24 to escape through during casting as shown in Figure 6.16.

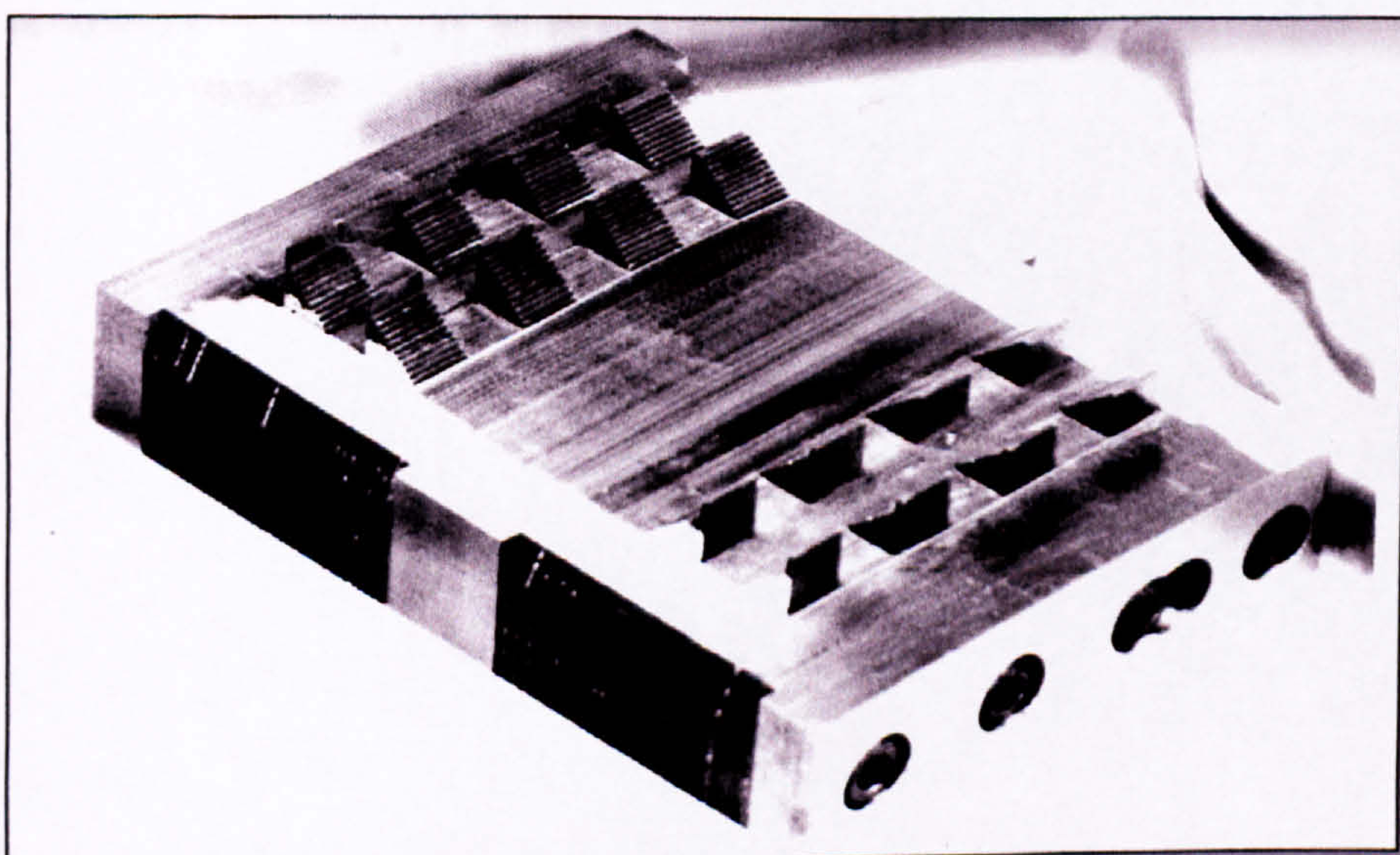


Figure 6.16 The laminate ejector insert prior to finishing

6.5.4 Finishing the Die Assembly

The inserts are held rigidly into the two bolsters by a series of H13 sliding wedges. The wedges not only fix the inserts in place but also provide additional compression to the laminate stacks as shown in Figure 6.17.

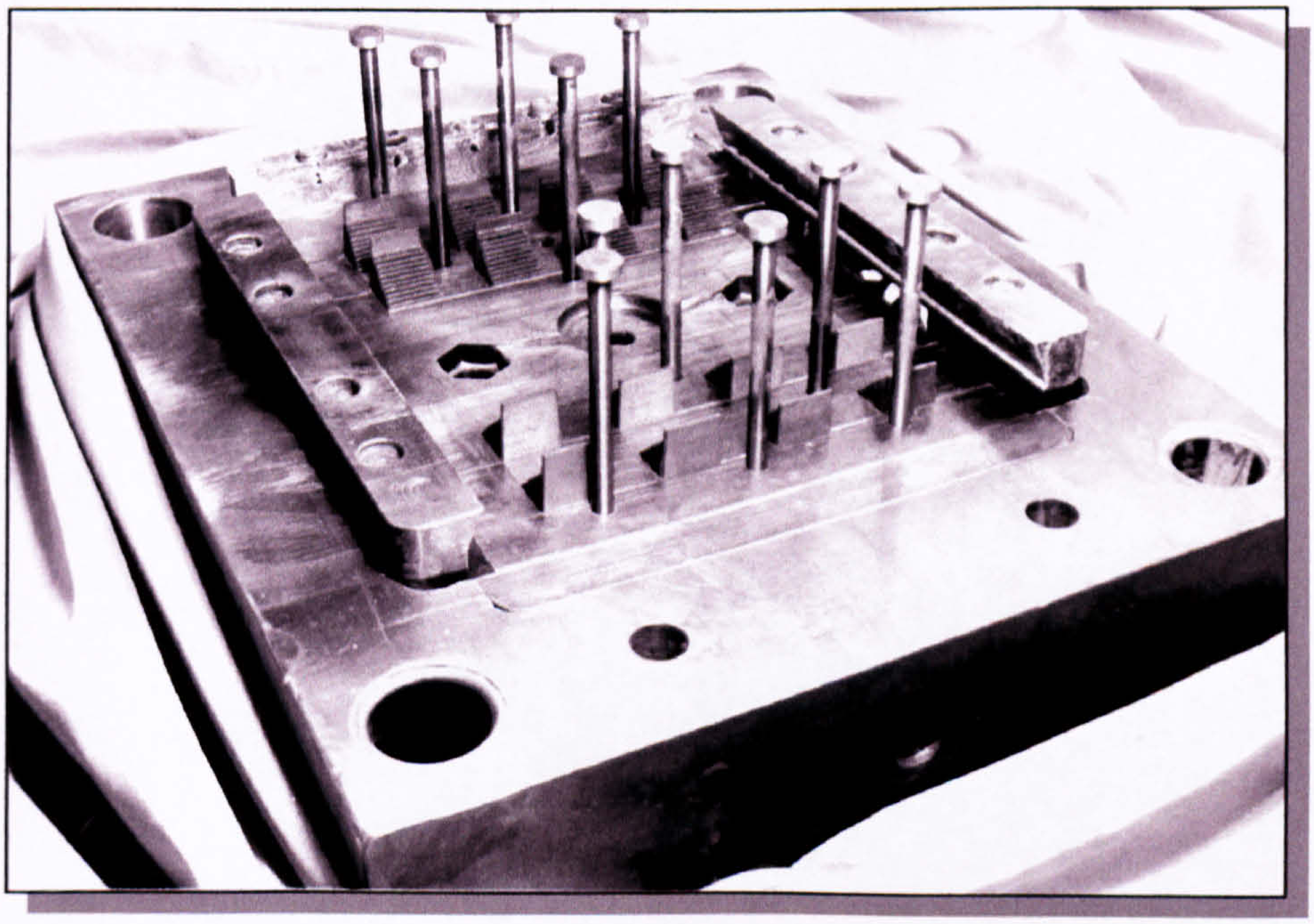


Figure 6.17 Location of side sliding wedges to fix the insert in place

Once securely fixed into its bolsters, a series of twelve 5mm through holes were drilled through the ejector die insert and through the solid bolster which contained it. These were reamed to ensure a smooth finish for the ejector pins to pass through and sit flush to the die surface and are shown in Figure 6.18.

Figure 6.18 also shows the completed laminate tool with the eight ramped up-stand features with their corresponding laminate protrusion ranging from 0mm, farthest away in the photograph, to 6mm in the foreground.

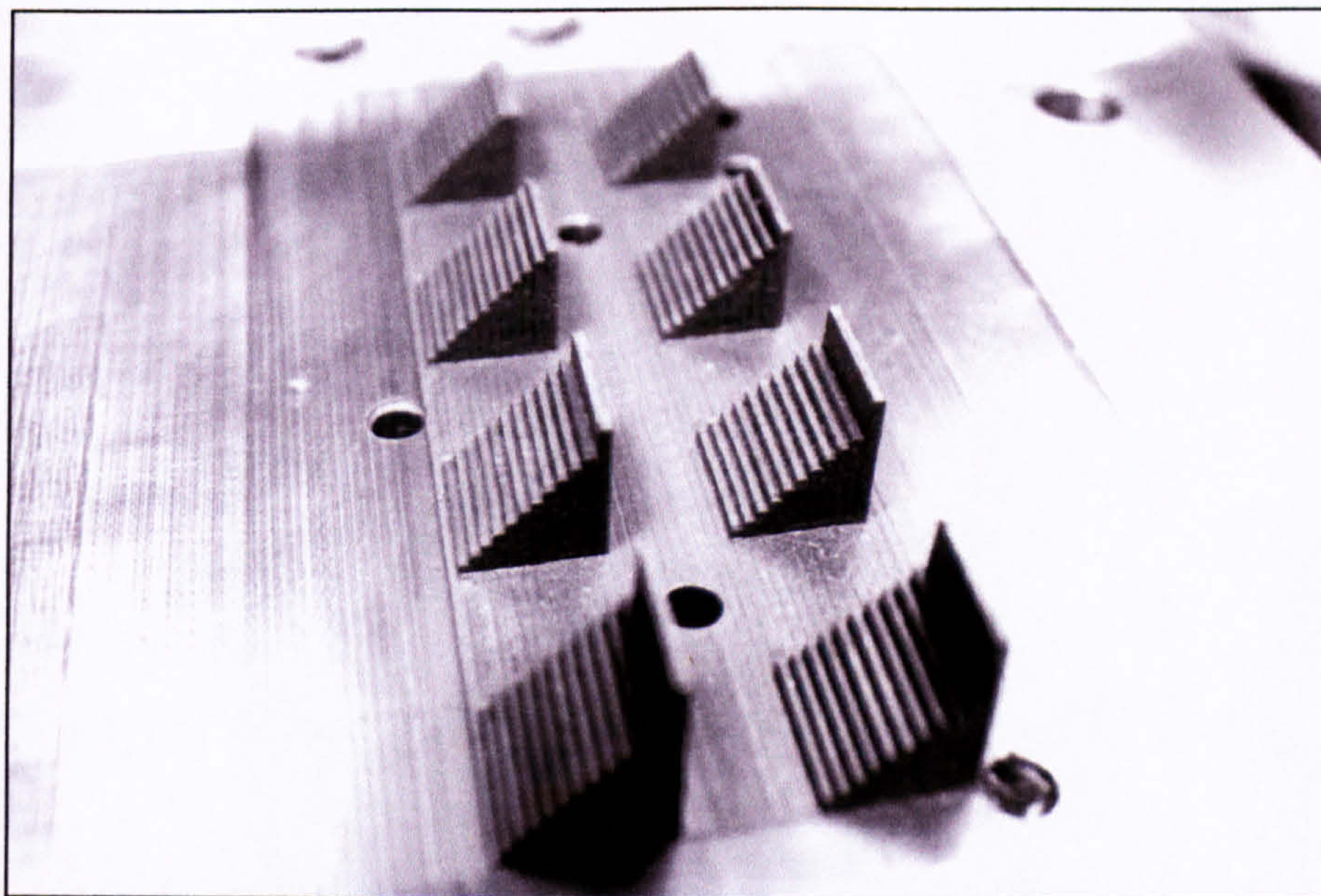


Figure 6.18 Through holes for ejector pins in laminate ejector die

Copper EDM electrodes were then produced to spark erode the inlet gate and runners required on the cover die. Work was required to include the thermo-couples and load cells and the completed die-set, with inserts and ejectors, is shown in Figure 6.19.

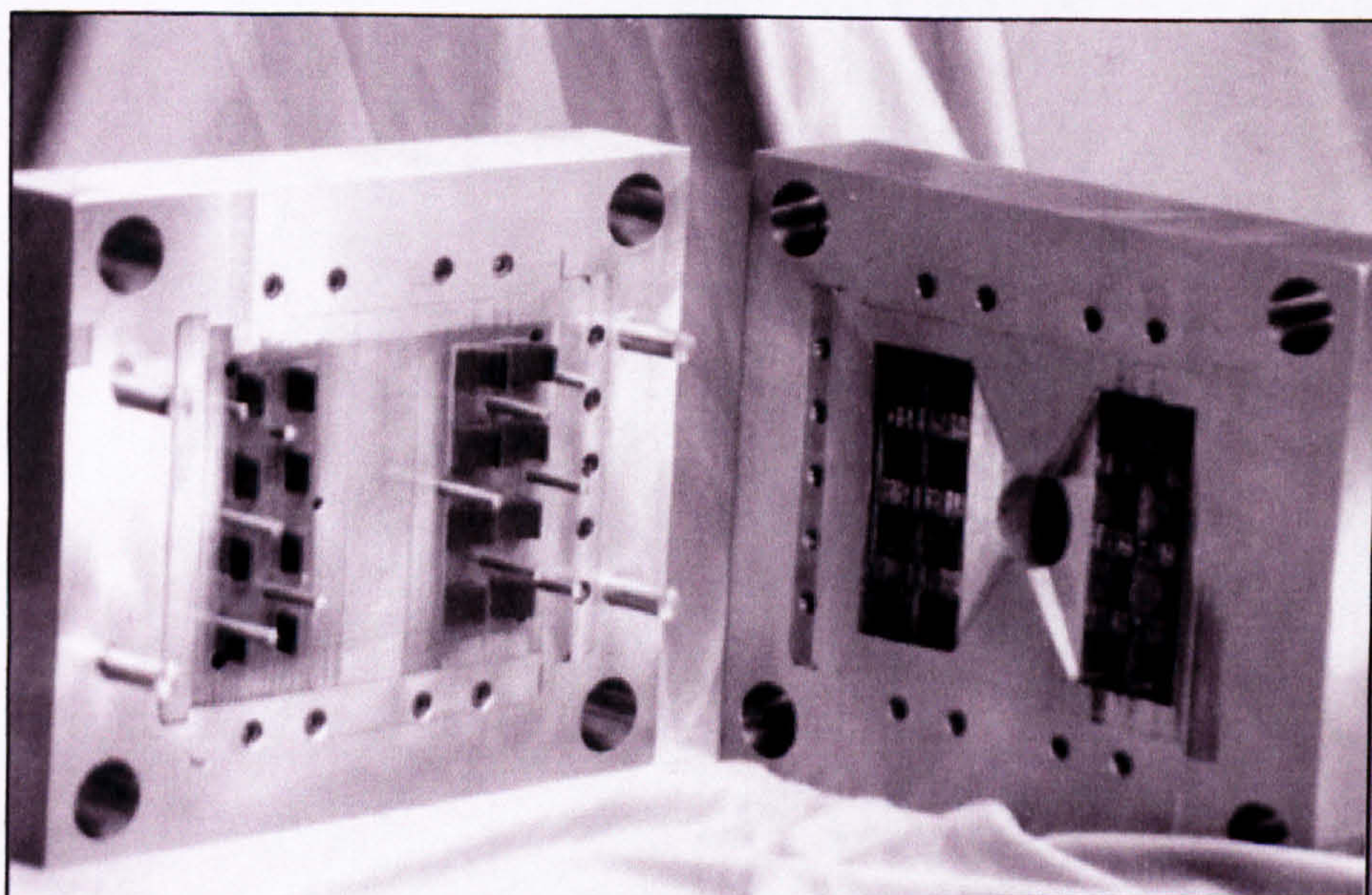


Figure 6.19 Completed laminate test-die

Chapter 7: Experiment One: To Examine an Un-bonded Laminate Test-die for High Pressure Die-casting

7.1 Introduction

Based on the methodology outlined in Chapter Six, this chapter describes the experiment to examine the feasibility of an un-bonded Laminate Tool specifically for High Pressure Die-casting (HPDC).

7.2 Aims of Experiment One

The aim of Experiment One was to investigate the fundamental question of whether an un-bonded laminate HPDC tool could withstand the forces imparted on the die's components.

As stated in Chapter Five, if the test-die could withstand the HPDC process then a further experiment (Experiment Two, Chapter Eight) would be conducted to observe, more closely, the affects of deflection on the die elements to attempt to define some form of design limit when constructing un-bonded laminate prototype tooling for HPDC applications. The ramp features used to explore this affect, in Experiment Two, were part of the same tool used in Experiment One. An array of eight different laminate protrusion heights were set on each ramp feature to attempt to identify the 'range' which ingress of molten alloy occurs between the laminates, through deflection, within an un-bonded laminate tool.

7.3 *Experimental Procedure*

The first part of Experiment One consisted of setting up and running the test-die. Observations included:

- Quality of the castings.
- Performance of the test-die.
- Control of the variables.
- Assessment of the laminate features within the test-die.
- Assessment of the EMB die-casting machine.
- Observations from the load cells and thermo-couples

If enough complete castings were generated from the test-die then those castings would be sectioned, as described in Chapter Six, so that the presence and size of any witness marks, as an indication of ingress, could be assessed. The actual location and height of each up-stand protrusion is shown on a CAD representation of the casting in Figure 7.1.

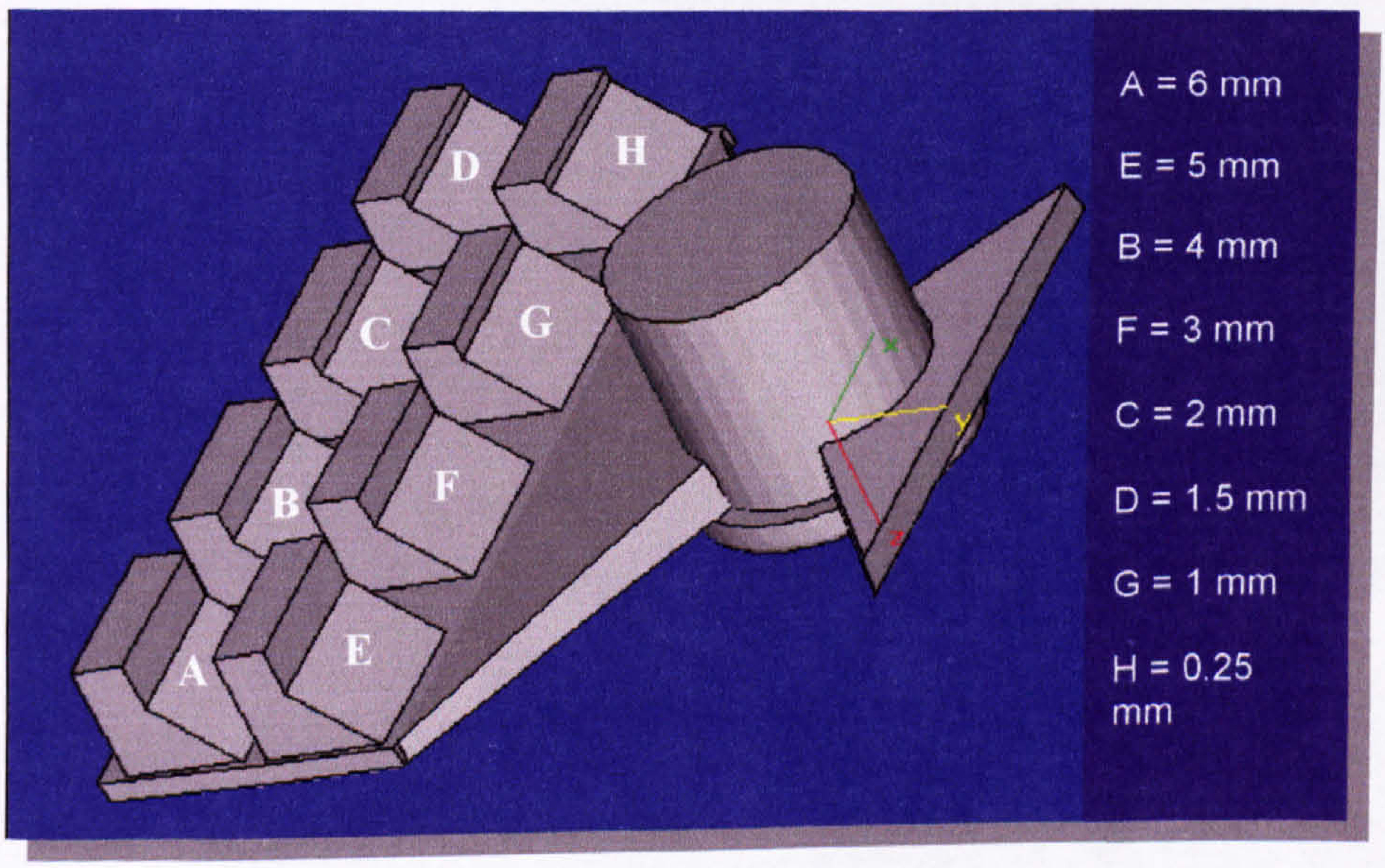


Figure 7.1 Location and height of each laminate protrusion on the casting

The coding (A through H) was used throughout the experiment, as well as for all subsequent experiments. The experiment was divided into runs (coded $R_{1.....N}$) of ten castings (coded $C_{1....N}$). The number of castings produced in a run, from the EMB machine, was dictated by the furnace capacity which held the molten LM24 alloy. This had been calculated at ten complete castings, including an excess amount to 'run-in' the die, to get it up to a steady temperature and to account for any spillage that occurred during the ladling process.

Furthermore, the type of release agent used during the casting process had to be specified. As stated in Chapter Four, the 3rd phase compaction used in the HPDC process is designed to compress the solidifying alloy within the die. This significantly reduces the amount of shrinkage experienced by the casting as the pressurised piston continues to feed molten alloy into the die cavity during cooling. There was a trade-off, however, when it came to the ejection of the casting. Any imperfections in either the ejector or cover die would cause friction between the die and casting. It is notoriously difficult to eject a casting from an HPDC die with a rough surface, even from the cover die where some shrinkage occurs. In the case of the laminate test-die, the surface was made up of the laser cut edges of the laminates. It was felt that any finishing, particularly to the ejector die, could have an adverse affect on the behaviour of the laminates which made up the ramp features. It was, therefore, important to use a release agent capable of ensuring smooth release of the casting to overcome any friction.

Standard release agents for HPDC are designed with aesthetics in mind. The die manufacturer will spend most of the time, when producing a die, in finishing the surface to a near mirror finish. Having a smooth die surface (0.025 - 0.1 R_a) naturally assists ejection of the casting and allows the die-caster to use a very thin-film, high temperature release agent which leaves virtually no deposits on the casting and results in a very clean finish. These release agents are based on Silicon or Polysiloxane compositions, if applied between shots, or, Teflon, if applied weekly. These agents would not assist ejection with the relatively coarse laser cut finish (6.3–12.5R_a) on the test-die.

The solution was to revert to the release agents used in the early days of HPDC. These are based on a colloidal suspension of graphite powder in some liquid media. The powder was traditionally suspended in oil but was eliminated from general use due to emissions as the oil burnt and also because of the black deposits of graphite that were entrained in the surface of the casting. For this experiment, aesthetics were not an issue and a solution of colloidal graphite (supplied by Foseco Ltd) suspended in 'suds' (a low emission emulsion of water and oil used in machining) was produced. The solution was trialed on a conventional HPDC die and proved excellent at coating the die surface and effectively filling any roughness in the die surface.

As previously stated, there was no die cooling in operation in the test-die and this meant that the mean die temperature increased by an average of 30^0C (established during the experiment) with each shot. If the die was run, with no pause between shots to allow the die to cool to its casting temperature of 175^0C-200^0C, then the temperature of the die would increase until it was too hot to chill the casting before ejection. The four thermo-couples were used to monitor the average die temperature so that the next cycle did not begin until the die had cooled sufficiently. Cooling was assisted with the water based release agent which was sprayed onto the die between shots.

The speed of the plunger, which forces LM24 into the die cavity during 2nd phase injection, had to be set, as it was an important variable in the process. A lever on the side of the EMB machine was marked off from 0 to 5. Exactly what plunger speed (m/s) each digit represented could not be established, even after consultation with EMB Ltd. They explained that the settings were arbitrary and would normally be set by an experienced operator who knew the machine. Changing the plunger speed does not normally affect the injection pressures, under normal conditions a steady 690 kPa is supplied to the intensifier at all times, but it does affect the injection velocity. After runs R_1, R_2 and R_3, an optimum plunger speed was set at position 3 (any higher led to flashing and any lower led to premature chilling). It took five complete runs ($R_{1....5}$) to establish reasonably consistent behaviour in the machine (and the author).

Establishing the cycle time was dependent on setting the plunger speeds and also establishing the length of time the casting needed to solidify before the die was opened to eject the casting (dwell time). This was not possible prior to the commencement of the experiment, as no data existed for the heat dissipation for this particular die. Establishing the dwell time was done after a couple of runs, using the Picolog thermo-couple data. For the first few runs, it was decided to err on the safe side and leave the dies closed for longer than ten seconds to ensure the casting had solidified.

Setting up each run took some considerable time, due to the age of the machine. Small gas burners were used to pre-heat the die, prior to the first shot in a run, and heating the die to the required 170^{0}C could take as long as two hours. Having just the one burner at the base of the die also meant that heating was very non-uniform and the temperature throughout the die had to be monitored to ensure that there was an even temperature distribution before casting could begin.

Many runs began and terminated, mainly due to the lack of experience the author had at the time when operating what was essentially, a process littered with variables. The physical act of ladling molten alloy from a furnace and pouring it into the small opening of the shot sleeve changes the nature of the alloy from one shot to another. Ladling too much material into the shot sleeve leads to excess flashing and too little alloy will chill very quickly, even before it enters the die. A machine of this age has no automatic control to hold variables such as furnace temperature, cycle times and operating pressures at a constant level between shots.

7.4 Results

7.4.1 Observations from R_1

This first run encountered numerous problems, mainly due to controlling the furnace temperature and initiating the data logging equipment prior to each casting. The parameters for each casting and observations for the entire run of three castings, are shown in Table 7.1.

Casting No.	Melt Temp ^{0}C	Shot Speed	Die Temp ^{0}C	Comments & Observations
C_1	695	0	175	Incomplete Casting, part froze prematurely
C_2	700	1	175	Incomplete Casting, difficulty filling shot sleeve
C_3	720	4	175	Incomplete Casting, increased plunger speed resulted in better filling, part seized

Table 7.1 Results from R_1

The experiment was terminated through an insufficient quantity of release agent applied to the dies which caused the casting to seize in the die. To remove the casting required the removal of the die from the EMB machine so that it could be stripped.

7.4.2 Observations from R_2

With the second run, it was decided to change the variables such as die temperature, melt temperature and plunger speed to observe any affects. The results are shown in Table 7.2.

Casting Code	Melt Temp ^{0}c	Shot Speed	Die Temp ^{0}c	Comments & Observations
C_1	700	3	175	Incomplete casting
C_2	720	3	180	Incomplete casting
C_3	700	3	180	Full casting, stuck in cover die, no release agent, casting destroyed on removal.
C_4	700	3	150	Incomplete casting, premature freezing of the part.
C_5	695	3	150	Incomplete casting, not enough LM24 in the ladle to complete shot
C_6	652	3	150	Incomplete casting, casting froze prematurely.
C_7	690	4	175	Incomplete casting
C_8	690	4	180	Incomplete casting, casting seized in die, experiment terminated.

Table 7.2 Results from R_2

As with the previous run, there was little success. It proved difficult to ladle the exact amount into the shot sleeve between shots. Any delay in the filling time led to the chilling of the alloy in the ladle. There was one complete casting, however, which seized in the die and was destroyed during its removal. Though no castings were generated in this run, the die was inspected for signs of permanent deformation in the ramp features which would prevent the casting from being ejected. No visible deformation was apparent on the laminate features in the die.

7.4.3 Observations from R_3

For the third run, a new ladle was constructed which would allow an exact measure of 0.3litres (the casting volume) of LM24 to be poured accurately into the shot sleeve between shots. This simple task greatly increased the quality of the castings.

An evaluation was made of the data from the thermo-couple readings gathered. Up until this stage, there had been no true way of gauging whether the casting had cooled sufficiently (dwell time) to solidify, before the dies were opened. If the dies were opened too quickly, the casting would not have cooled enough and there was a risk that the ejectors would punch their way through the casting, instead of pushing it off the features in the ejector die.

From the two previous runs, the readings from the four thermo-couples were plotted to find a correlation between the measurements in the die and the point at which dies could be safely opened. The graph for R_2 C_2 was plotted from the thermocouple data. This was the first complete casting and is shown in Figure 7.2. The four thermo-couple positions (discussed in Chapter Six) are labelled centre, two, three and farthest (from the inlet gate), in Figure 7.2, and lie 5 mm below the surface.

The 'centre' thermo-couple, on the graph, is located at the point closest the shot sleeve in the die and this thermo-couple, naturally, goes through the greatest temperature increase. The 'farthest' thermo-couple is located at the rear of the die cavity and detects heat last, as it is the furthest point from the shot sleeve.

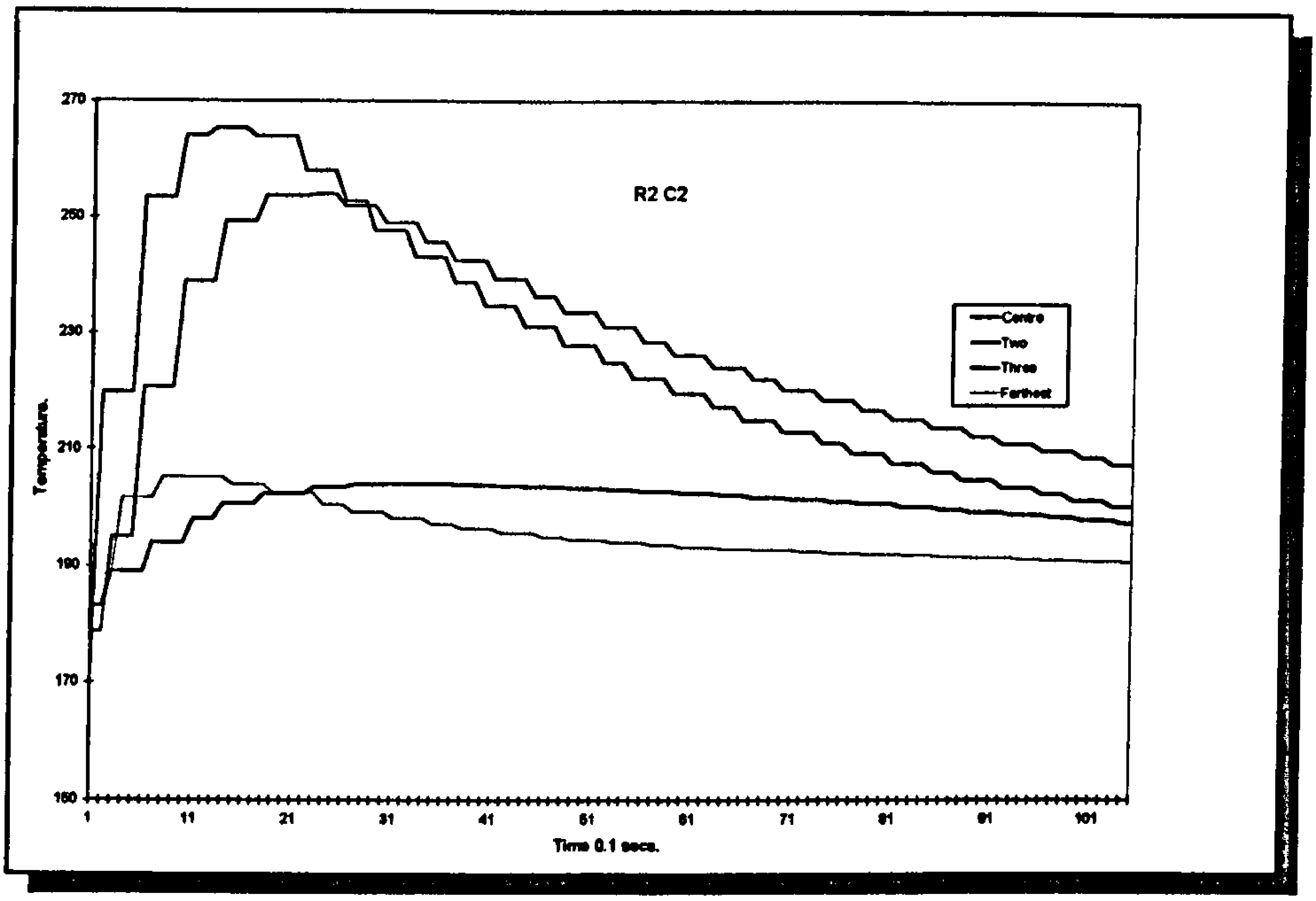


Figure 7.2 Thermo-couple readings for casting R_2 C_3

The Picolog software samples at 0.1 second intervals (shown in Figure 7.2). The initial rise in temperature quickly peaked and returned to the start temperature, for the four thermo-couples, over a period of 10 seconds. Ten seconds was, therefore, deemed the shortest dwell time before the dies were opened and approximately one minute before the die could be closed for the next shot (based on Picolog readings). The observations from R_3 are shown in Table 7.3.

Casting Code	Melt Temp ^{0}c	Shot Speed	Die Temp ^{0}c	Comments & Observations
C_1	700	4	175	Complete casting, some flashing
C_2	700	2	175	Complete casting, more release agent required in dies
C_3	700	2	175	Incomplete casting, casting froze to ejector die
C_4	700	2	175	Complete casting
C_5	700	3	175	Complete casting, misalignment in the ejector plate, experiment terminated

Table 7.3 Results from R_3

Four complete castings were produced and it was hoped to continue the run for ten complete castings. After casting C_5, casting alloy worked its way into the ejector mechanism and the die seized. This required a complete strip-down of the ejector die before the next run could commence. The first castings were heavily coated with the graphite release agent and this was reduced through the run until C_4 and C_5 appeared as relatively clean castings.

7.4.4 Observations from R_4

During runs $R_{1\text{-}3}$, the speed of the plunger had been varied to control the amount of flashing which occurred. It was decided to hold the speed at a constant level for R_4 and see if castings could still be generated. The results are shown in Table 7.4.

Casting Code	Melt Temp ^0C	Shot Speed	Die Temp ^0C	Comments & Observations
C_1	700	3	175	Complete casting, large flash
C_2	710	3	180	Incomplete casting, large flash, adjusted tie bars to reduce flashing
C_3	770	3	180	Complete casting, large flash still, furnace temp may be too high.
C_4	720	3	180	Complete casting, large flash at top of die, platens misaligned, experiment terminated.

Table 7.4 Results from R_4

Some work was required to the die after the previous run. When the die was mounted back on the machine, the toggle mechanism was 'locking out' but a gap along the parting line appeared in the upper half of the die. Complete castings were produced but too much alloy was being lost through the gap, as flashing, and the experiment was terminated until the dies could be re-mounted and the gap closed.

7.4.5 Observations from R_5

The test-die was run again with some success. Complete castings were produced but, again, the run was impaired with excessive flashing along the parting line. Observations are shown in Table 7.5.

Casting Code	Melt Temp ^{0}c	Shot Speed	Die Temp ^{0}c	Comments & Observations
C_1	695	3	175	Complete casting, low flash, temperature rising in furnace quickly to 725^{0}C
C_2	712	2	175	Incomplete casting but a clean finish on casting.
C_3	710	2	180	Complete casting, large slug, ejected well, low flash.
C_4	720	2.5	190	Complete casting, evidence of premature chilling in die, increased flashing.
C_5	720	3	175	Complete casting, clean cast, furnace thermocouple may be misreading.
C_6	740	2	180	Complete Casting, very large flash, long slug and the casting froze in the cover die, experiment terminated.

Table 7.5 Results from R_5

The run was, again, terminated prematurely, due to a seized casting. An investigation for the possible cause of excess flashing revealed that the thermo-couple incorporated into the furnace was damaged and was giving erroneous readings. As a result, the furnace temperature was considerably hotter than 700^{0}C and closer to 850^{0}C at one point. This led to a severe degradation of the alloy. The excessive residual heat in the alloy would explain the flashing, as the alloy remains fluid for longer in the die cavity during 3rd phase compaction.

7.4.6 Observations from R_6

During the sixth run, flashing was still a concern and the effectiveness of the pneumatic toggle mechanism was suspected as a possible cause. The strategy for run R_6 was to concentrate on ladling in the correct quantity of LM24 into the shot sleeve. Filling the correct amount of alloy into the shot sleeve would reduce the flashing. Observations are shown in Table 7.6.

Casting Code	Melt Temp ^{0}c	Shot Speed	Die Temp ^{0}c	Comments & Observations
C_1	695	3	185	Complete casting, slightly pitted and poor finish, die maybe too hot.
C_2	710	3	185	Incomplete casting, melt temperature too high, burning of release agent.
C_3	700	3	180	Incomplete casting, die too hot, ladling quantity too low, less burning.
C_4	695	3	175	Incomplete casting, correct quantity, poor finish.
C_5	695	3	175	Incomplete casting, incorrect quantity ladled into shot sleeve.
C_6	695	3	175	Incomplete casting. Inconsistencies in machine, experiment terminated.

Table 7.6 Results from R_6

R_6 proved very difficult to control, the furnace was still suspected of over-heating but it also proved hard to ladle the exact amount into the die consistently. The laminates which comprised the up-stand protrusions on each ramp feature were showing signs of permanent deformation, with evidence of ingress of alloy between the protrusions and the ramp features.

Unfortunately, the only complete casting which was produced was in too poor a condition to analyse for witness marks and the remaining castings were incomplete. It was felt that enough deformation and ingress had occurred in the laminate protrusions to justify a new set, in case the next run produced a complete set of castings which could be analysed.

As to why deformation, and subsequent ingress, had occurred during this run, and not its predecessors, was unclear. The previous run had been terminated, prematurely, through a seized casting and its removal from the cavity could have resulted in some damage which led to deformation and ingress.

7.4.7 Observation from R_7

The only safe way to ensure a complete casting was to overfill the shot chamber. The major drawback to this approach was that if too much casting alloy was placed in the shot sleeve there was a risk that the plunger would not extend far enough down the shot sleeve to initiate 3rd phase compaction. A hand held thermo-couple was used to control the furnace temperature. The time between each shot was delayed until the variables (die and furnace temperature) were correct. Observation are shown in Table 7.8.

Casting Code	Melt Temp ^{0}c	Shot Speed	Die Temp ^{0}c	Comments & Observations
C_1	695	3	175	Complete casting, some flashing, long slug from over filling.
C_2	695	3	175	Complete casting, exact amount of LM24 in shot sleeve, too much graphite.
C_3	695	3	175	Complete casting, long slug, some flashing, over filled.
C_4	695	3	175	Complete casting, just enough alloy in sleeve, some burning.
C_5	695	3	175	Complete casting, clean casting, no flashing, exact amount.
C_6	695	3	175	Complete casting, large flash, burning of the release agent.
C_7	695	3	175	Complete casting, reduced amount in shot sleeve, very clean casting.
C_8	695	3	175	Complete casting, reduced release agent further, very clean, large flash.
C_9	695	3	175	Complete casting, very clean casting, low flash.
C_{10}	695	3	175	Complete casting, clean casting, flashing increasing.

Table 7.8 Results from R_7

The first set of ten complete castings were produced and justified the decision to replace the laminate protrusions. Ladling quantities still fluctuated but, on each shot, enough alloy was placed in the shot sleeve. The furnace temperature was fluctuating erratically throughout the run and required constant monitoring to ensure a constant temperature.

Casting R_7 C_1 is shown in Figure 7.2.

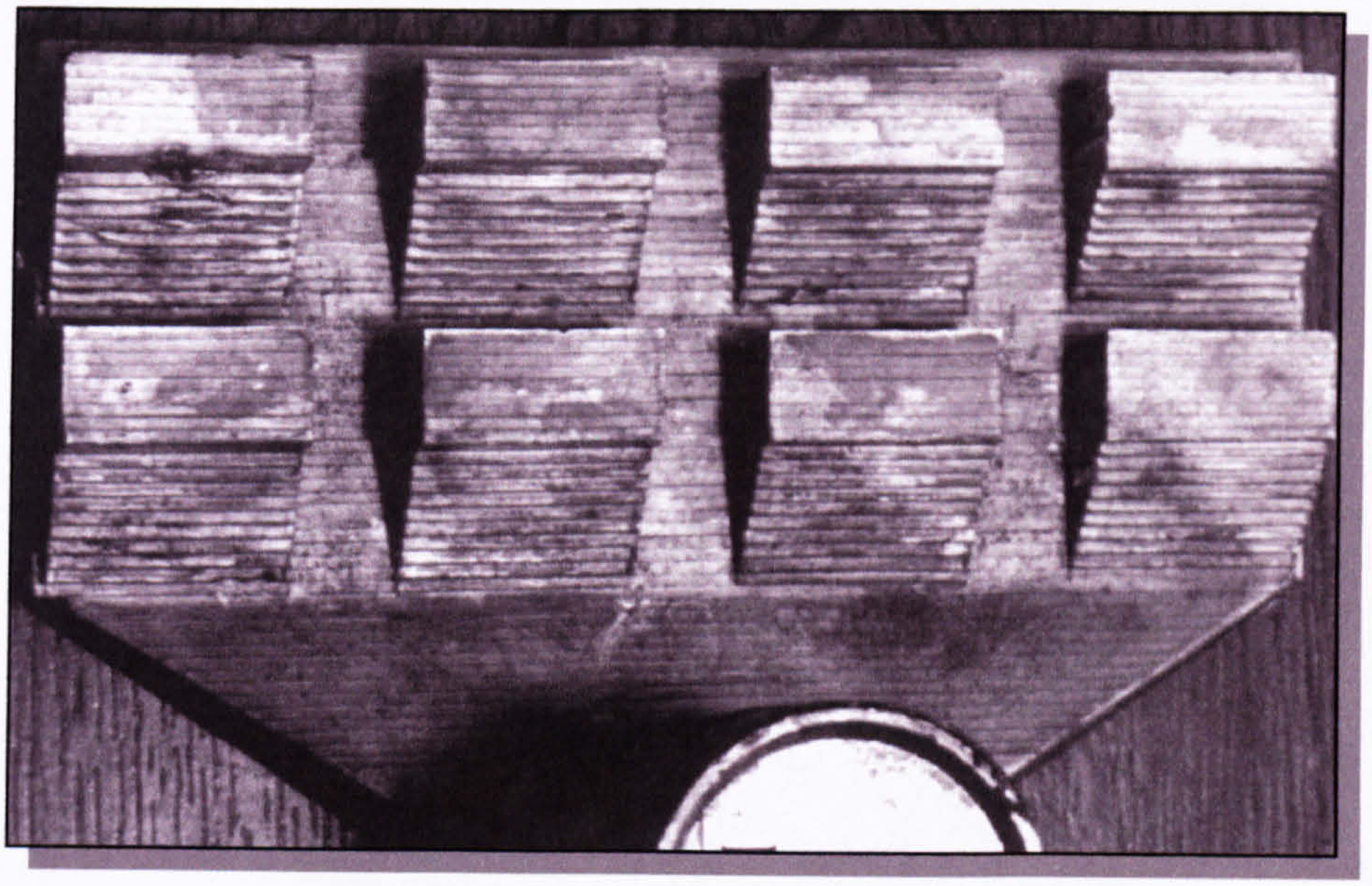


Figure 7.2 Casting R_7C_1 from first run of ten complete castings

7.4.8 Results of Deformation and Ingress of Laminates in R_7

The second part of Experiment One was to look at the affect of deflection and measure any subsequent witness marks, as an indication of the range of heights that ingress was occurring for 1mm thick steel sheet. These data will be used to set the range of protrusion heights for a more in depth study in Experiment Two.

The final run, R_7, had a new set of laminates to replace those which had been damaged up to that point and it was this set of laminates from which the first set of ten complete castings were produced. It was these castings which were sectioned, as described earlier, to examine any witness mark left as an indication of the degree of deflection on each of the laminate protrusions on each ramp feature. Figure 7.3 and 7.4 show the casting sectioned and the view of the witness mark which was measured.

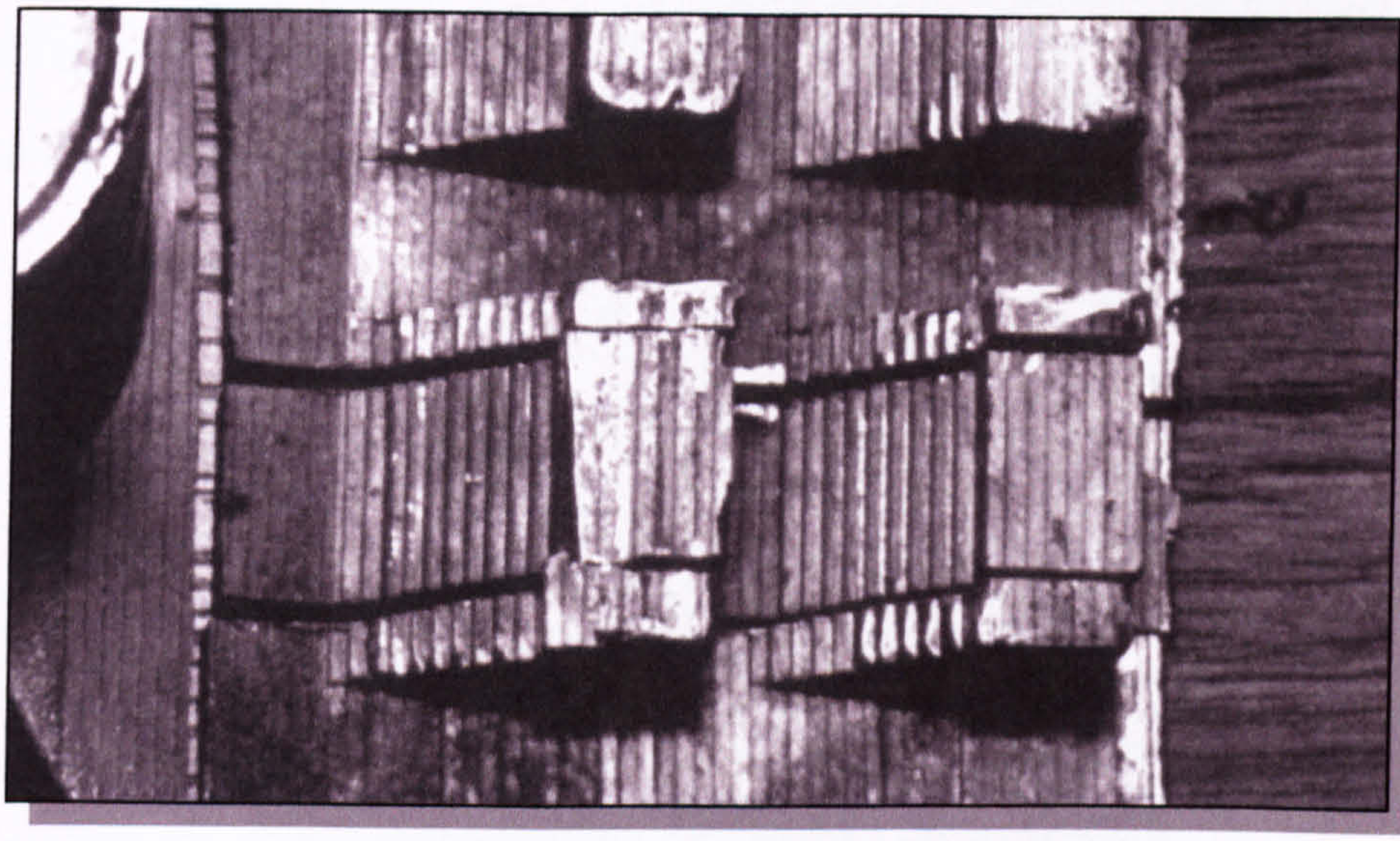


Figure 7.3 Sectioned casting for measurement of witness marks

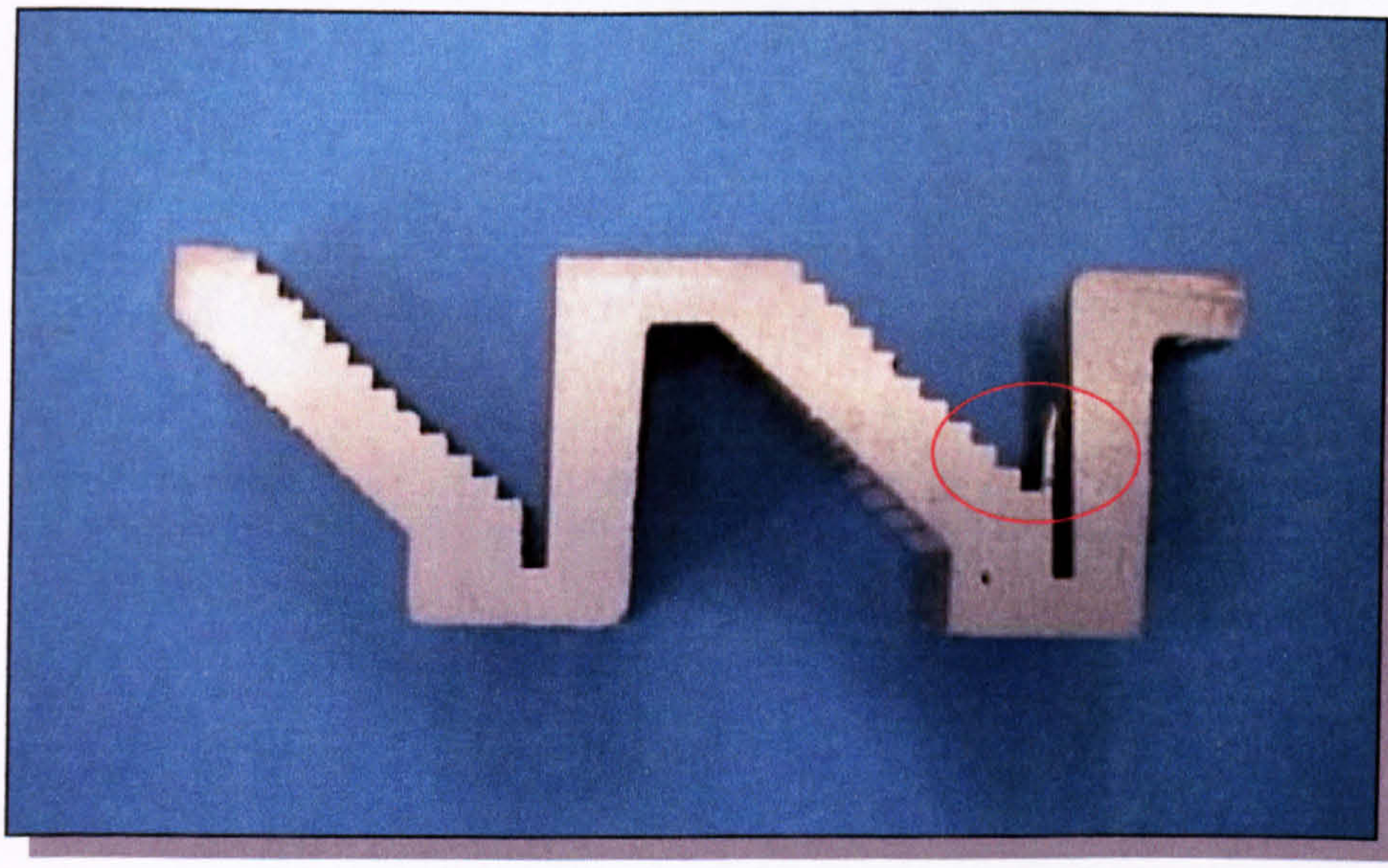


Figure 7.4 Cross-section of sectioned casting showing witness mark

The width of each witness mark was measured, using a Vernier microscope at 15× magnification with a resolution down to approximately 0.01mm. Measurements were taken from each witness mark and the mean ingress calculated for each up-stand location over all ten castings.

Table 7.9 shows the width of the measured witness marks which indicate the degree of deflection at that location. Ingress did fluctuate, at each up-stand location throughout the run, probably due to the inconsistencies in the pneumatics in the EMB machine.

Casting Number	6.00 mm Up-stand 'A'	4.00 mm Up-stand 'B'	2.00 mm Up-stand 'C'	1.50 mm Up-stand 'D'
R_7C_1	0	0.05	0	0
R_7C_2	0	0.05	0	0
R_7C_3	0.05	0.1	0	0
R_7C_4	0	0.06	0	0
R_7C_5	0	0	0	0
R_7C_6	0	0.05	0	0
R_7C_7	0	0	0	0
R_7C_8	0	0.07	0	0.07
R_7C_9	0	0.05	0.04	0
R_7C_{10}	0	0.06	0.05	0
Mean	**0.01**	**0.05**	**0.01**	**0.01**

Casting Number	5.00 mm Up-stand 'E'	3.00 mm Up-stand 'F'	1.0 mm Up-stand 'G'	0.25 mm Up-stand 'H'
R_7C_1	0	0.1	0.05	0.05
R_7C_2	0.05	0.07	0.07	0
R_7C_3	0.05	0.08	0.07	0.07
R_7C_4	0.1	0.15	0.05	0.11
R_7C_5	0.3	0.16	0.07	0.05
R_7C_6	0.05	0.06	0.05	0.09
R_7C_7	0.05	0.11	0.06	0.05
R_7C_8	0.1	0.15	0.09	0.07
R_7C_9	0.07	0.11	0.06	0.06
R_7C_{10}	0.08	0.08	0.05	0.07
Mean	**0.09**	**0.11**	**0.06**	**0.06**

Table 7.9 Mean ingress of ten castings from R_7

Initial observation of these data shows more activity in the ramp feature E, F, G & H than in features A, B, C & D. The most likely explanation being that these features were closer to the inlet gate than A, B, C & D. In addition, there were definitely up-stand features which suffered no deflection and features which did deflect.

It was hoped that when these data were plotted, in protrusion height order (i.e. A, E, B, F, C, D, G & H that represent 6, 5, 4, 3, 2, 1.5, 1, & 0.25mm respectively), there would be a point on the graph which clearly showed a 'jump' in the readings. This would be the height at which ingress began to register, as the protrusion height increased. This graph is shown in Figure 7.5.

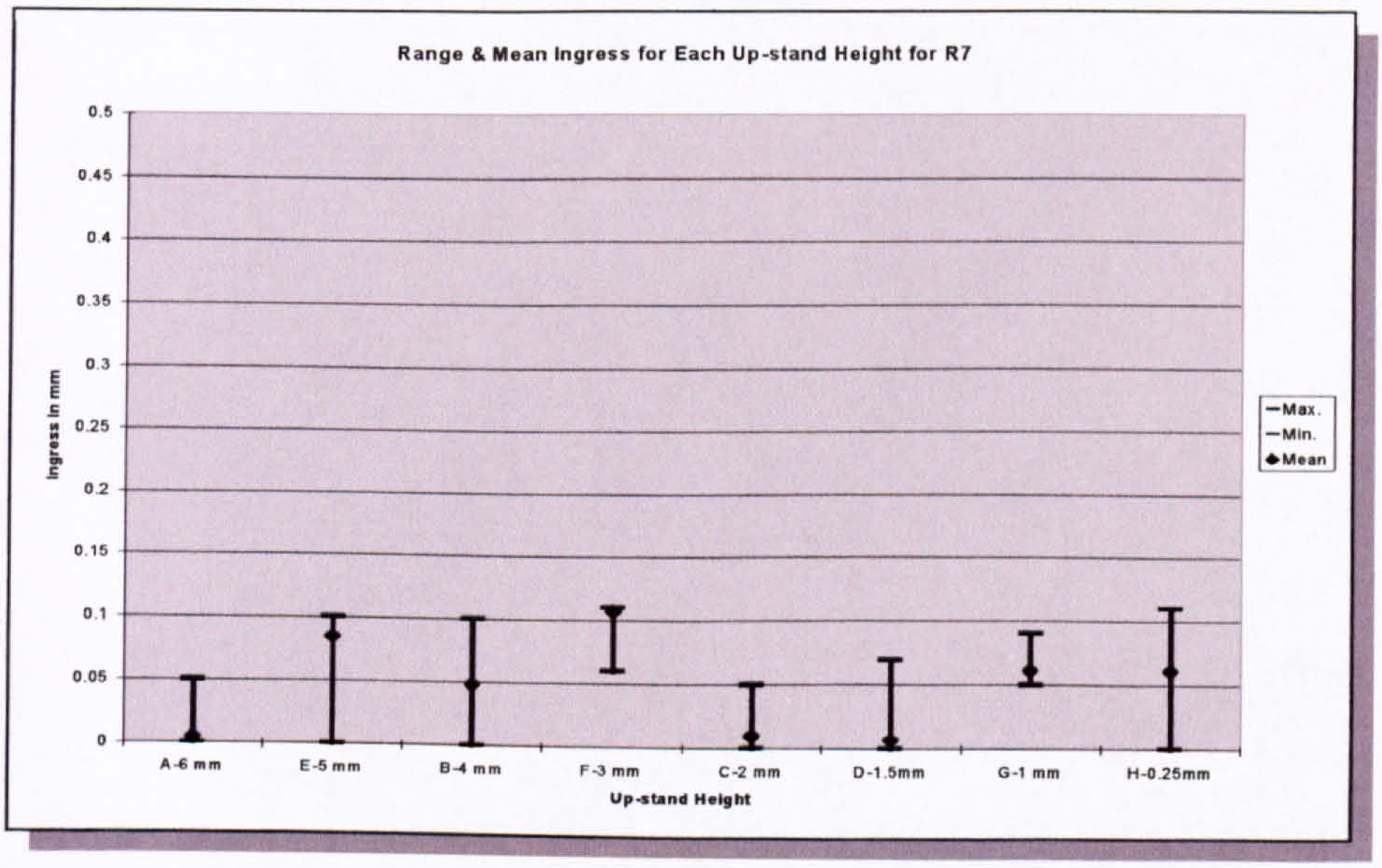


Figure 7.5 Mean ingress for ten castings from R_7

The graph shows three measurands for each up-stand location. These are the maximum and minimum ingress readings and the mean ingress over all ten castings at each up-stand location (A-H). A close range is indicated for most of the up-stands. However the magnitude of deflection appears to fluctuate erratically over the different protrusion heights. Ingress should be most apparent on the 6mm protrusion and least apparent at the 0.25mm. From these results, this did not happen and ingress occurred at different up-stand locations, independent of the protrusion height. This was an indication that further variables may be influencing the results.

7.5 *Discussion*

A total of 24 complete castings were produced from the laminate test-die, including a complete run of ten castings. During all seven runs, at no point did the die fail to the degree that castings could no longer be produced. However, deformation of some of the laminate up-stand features did occur, leading to ingress of LM24 between the laminates.

For runs R_1 through R_6, the laminates which made up the protrusions above the ramp features were not changed, as each run suffered problems, and to replace the laminate after each run was deemed impractical. Measuring the castings for visible witness marks was impossible, as so many castings were incomplete. Figure 7.6 shows the nature of deformation and subsequent ingress on the laminates after the first six runs.

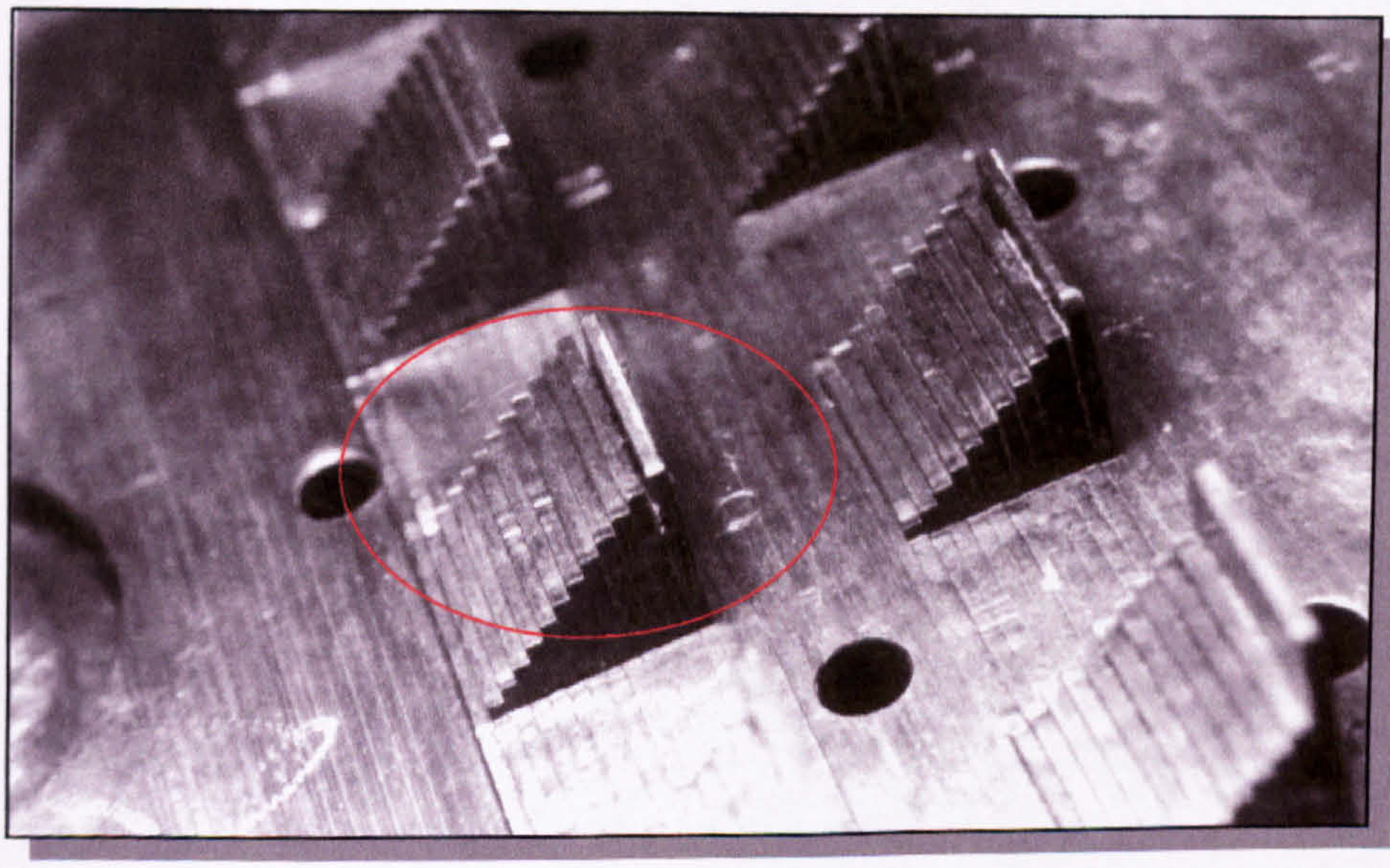


Figure 7.6 Permanent deformation of laminate

The laminates in this test-die were dismantled to show the depth of penetration of alloy into the subsequent gap which opened up between the laminate protrusion and ramp feature. Figure 7.7 shows a thin layer of LM24 deposited in the gaps which opened up, due to extended use in the first six runs.

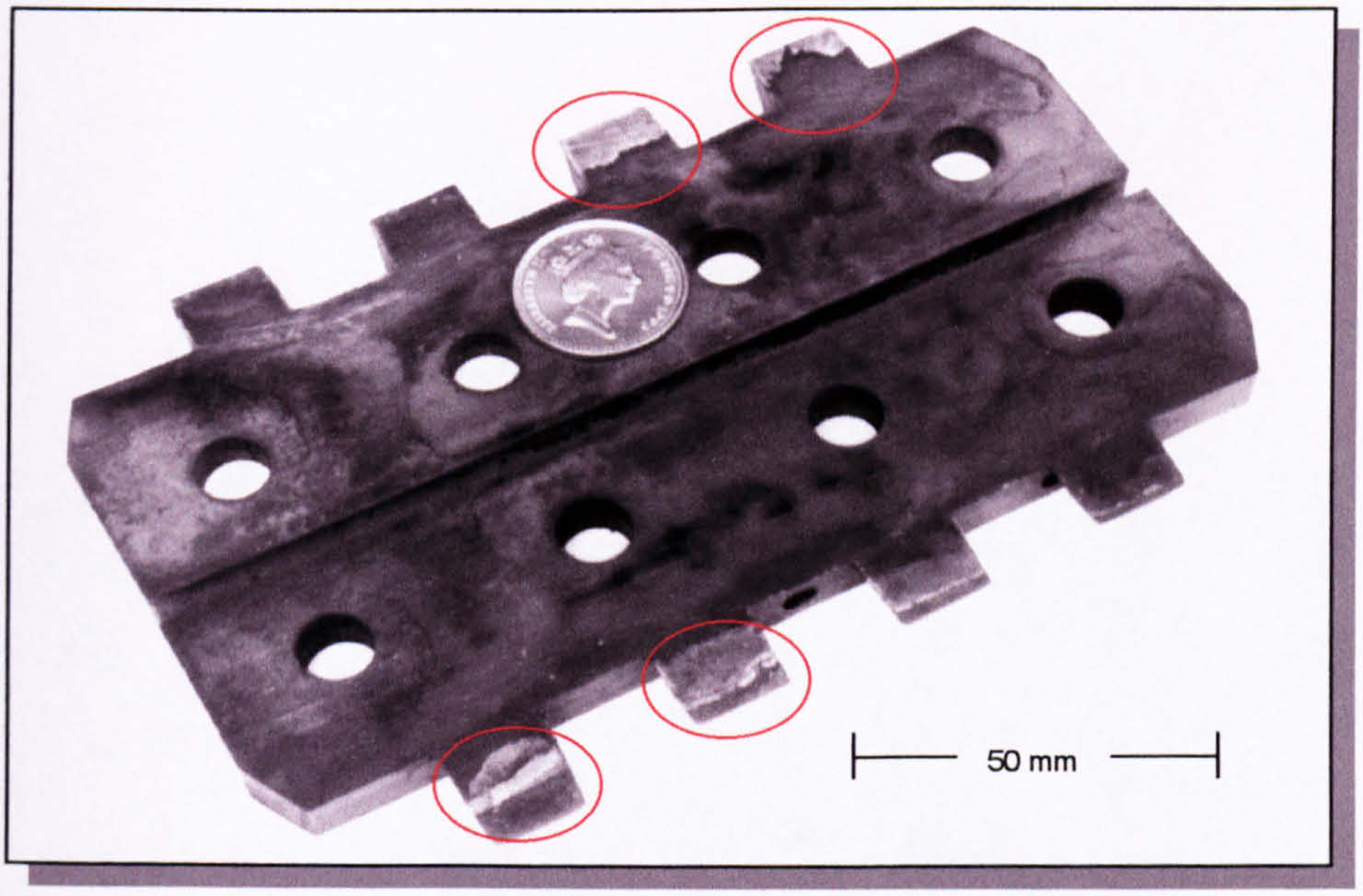


Figure 7.7 Dismantled laminate protrusion showing extent of ingress

Run R_7 represented the first complete set of castings, with new laminate protrusions present, in which the effects of deformation during HPDC conditions could be observed. Figure 7.8 through 7.11 show the effects of prolonged exposure to HPDC conditions to each ramp feature denoted in Figure 7.1.

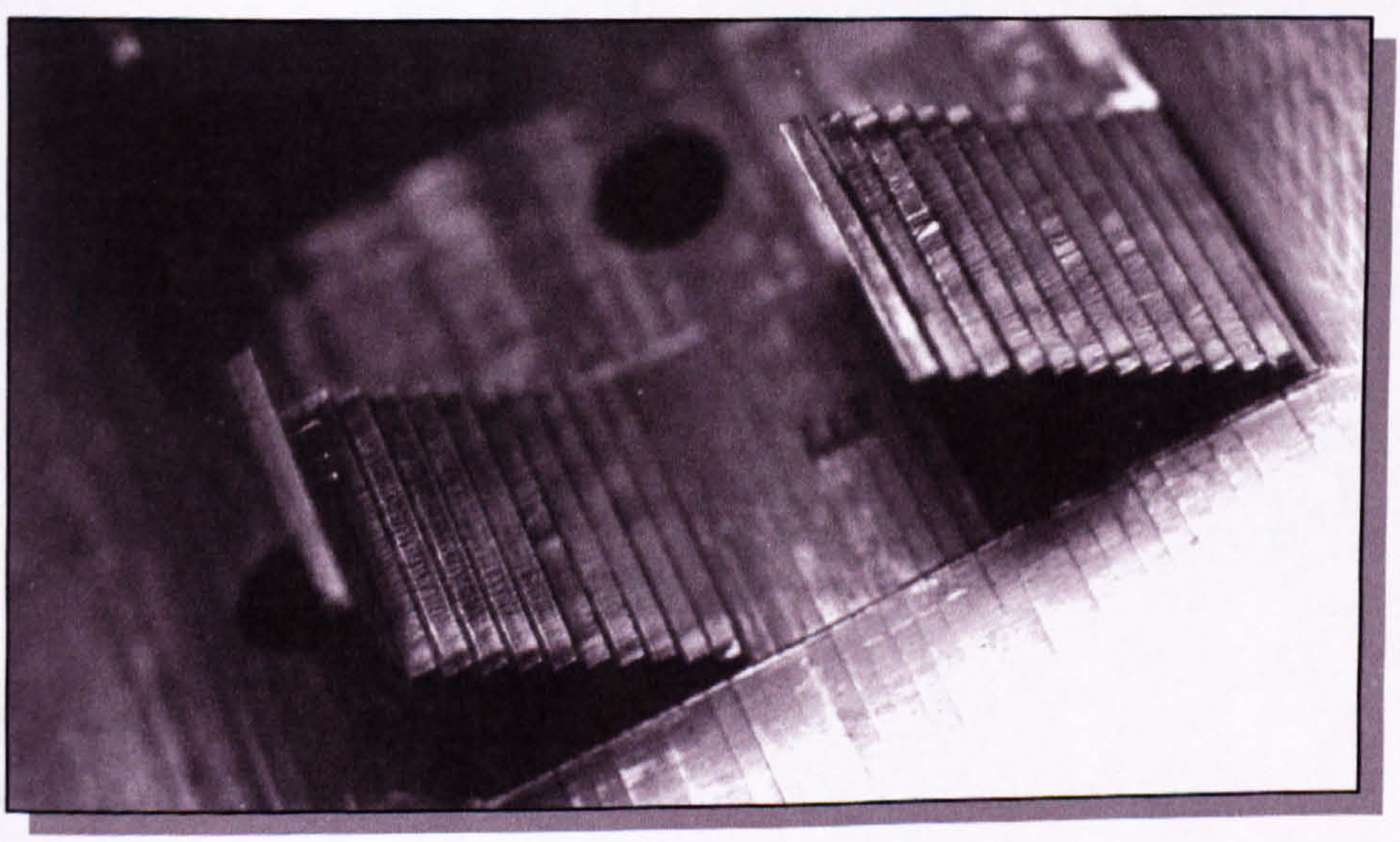


Figure 7.8 Ramps A and E after ten complete castings

A visible gap had appeared in ramp feature E, in Figure 7.8, indicating that this laminate had suffered permanent deformation through the action of deflection and subsequent ingress. The following photographs show no such, visible, deformation even though there was evidence of deflection on the casting in the form of witness marks. This phenomenon will be explored further in the next experiments.

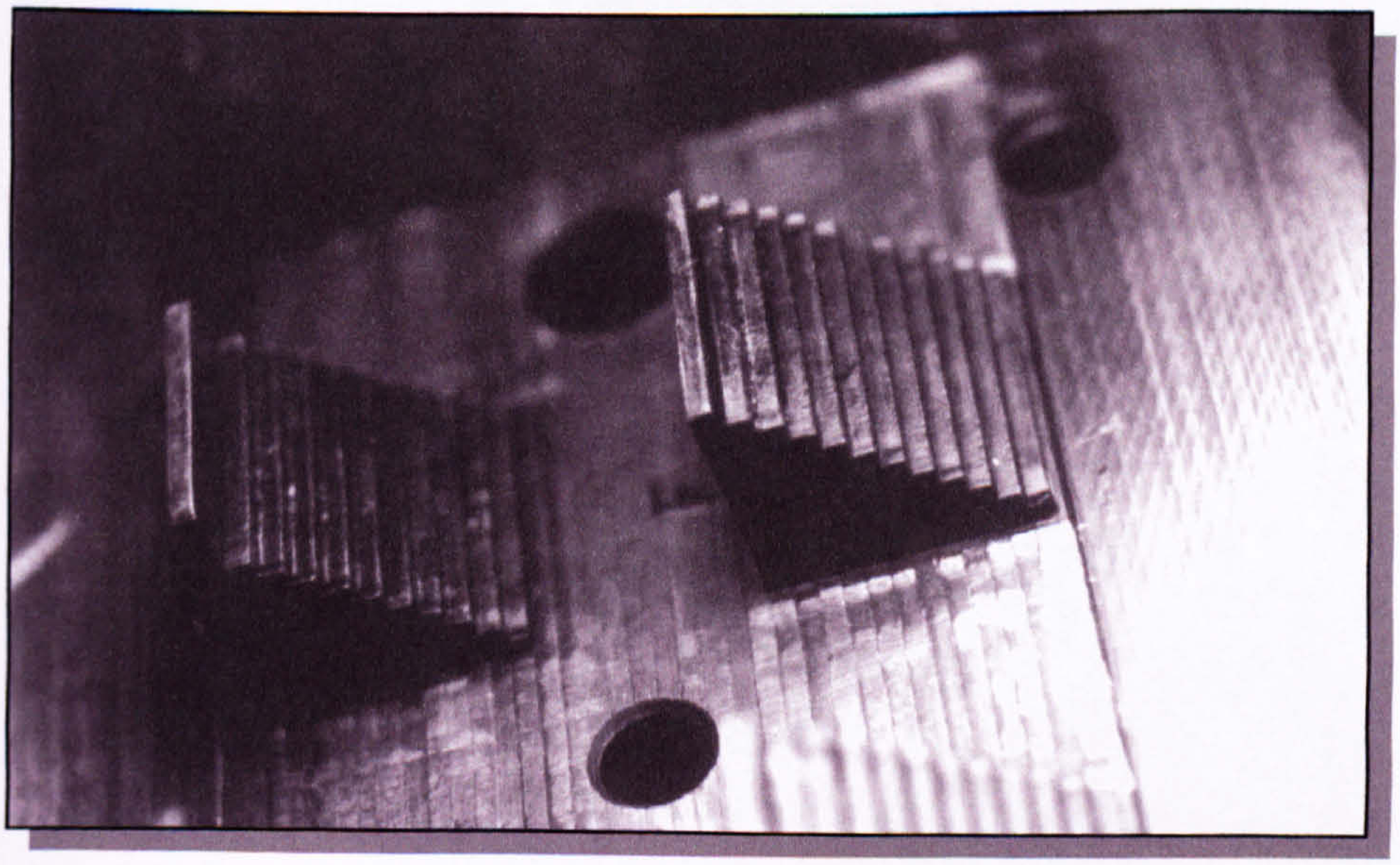


Figure 7.9 Ramps B and F after ten complete castings

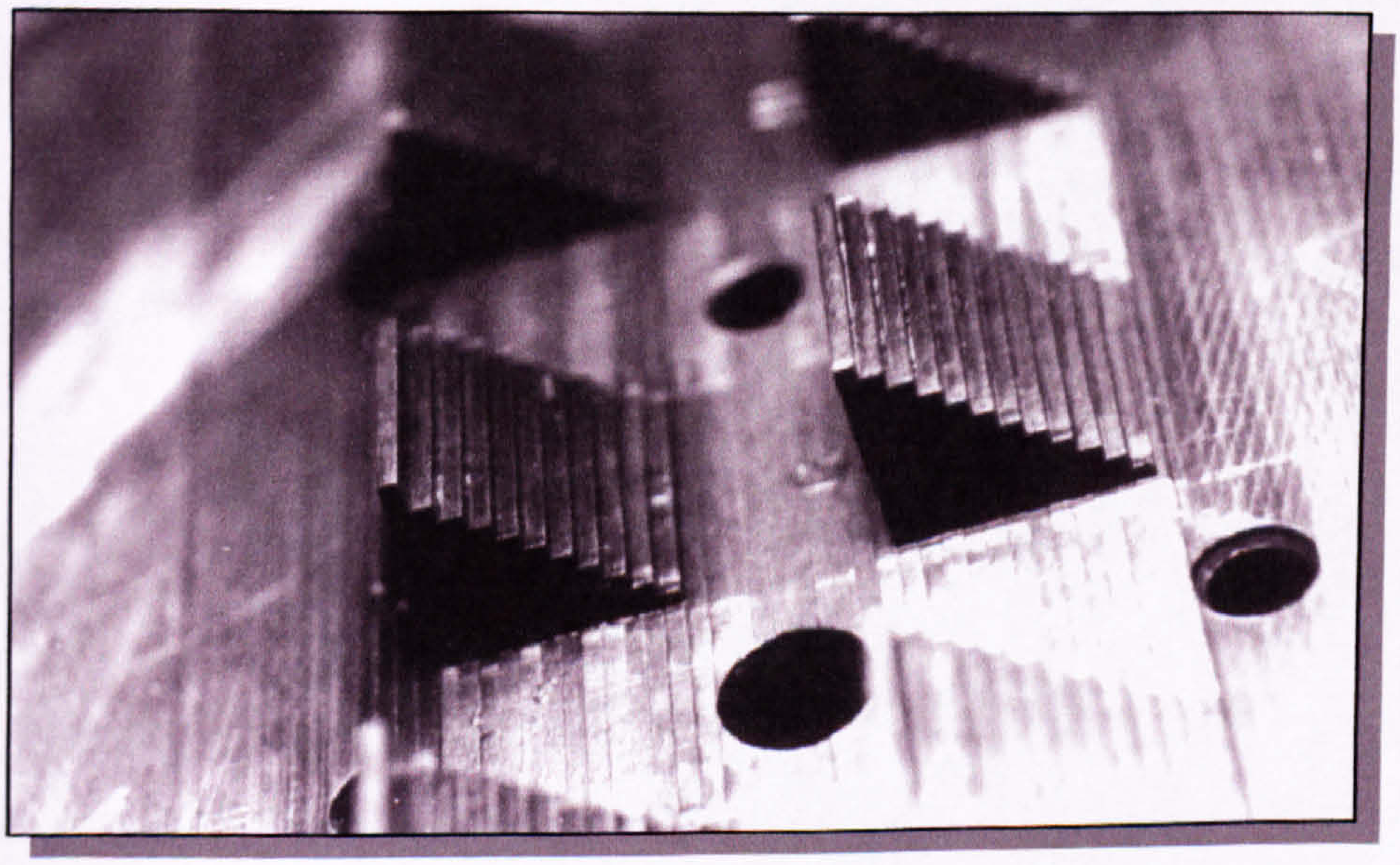


Figure 7.10 Ramps C and G after ten complete castings

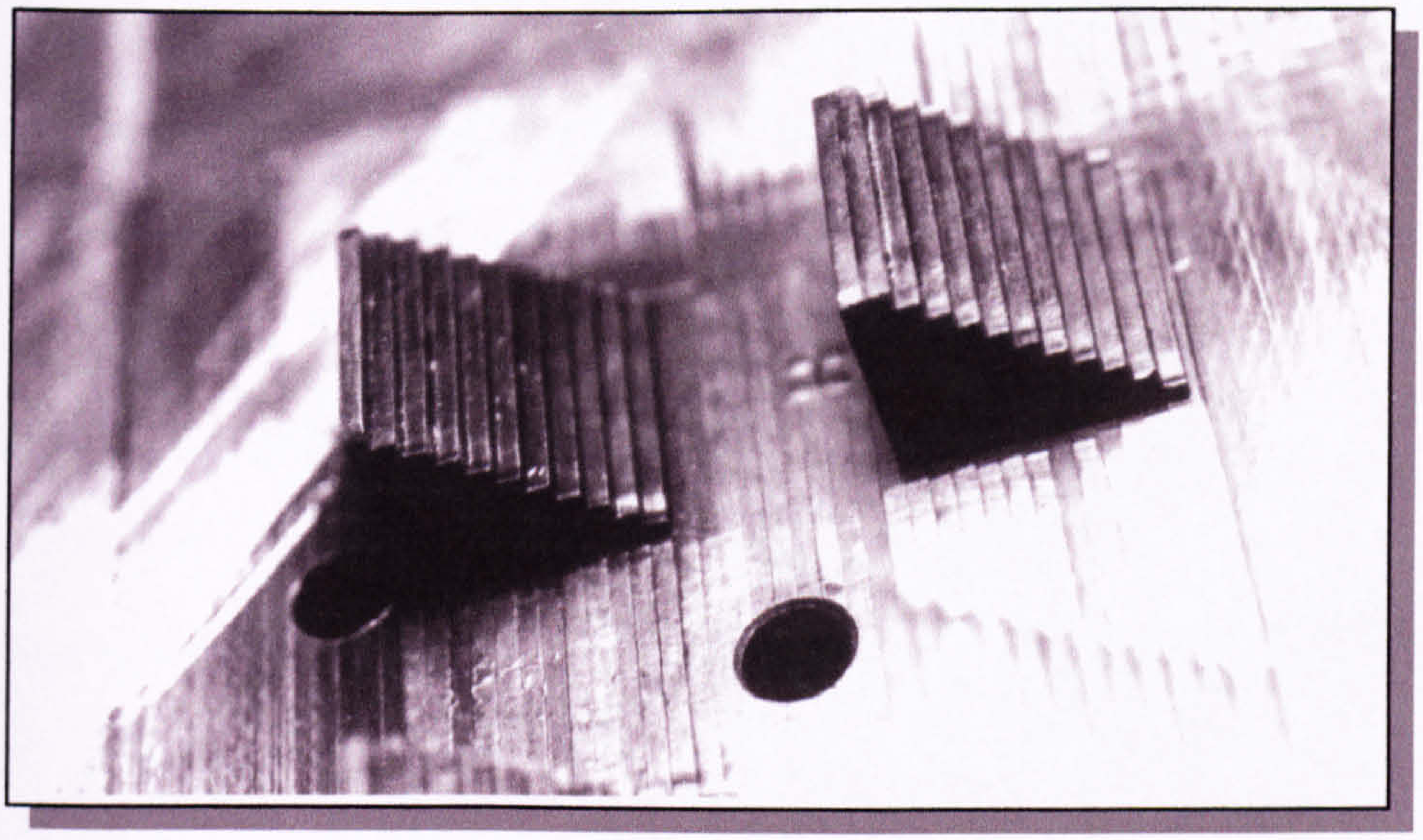


Figure 7.11 Ramps D and H after ten complete castings

On all eight ramp features, except ramp E, there were no adverse signs of permanent damage from the ten castings. Deflection and some ingress did occur but, in all cases, the molten alloy appeared to have been ejected as the laminate protrusion sprung back to its vertical position.

A second complete run was planned but, during the initial set-up, the furnace 'shorted', effectively putting the unit out of action until it could be re-built. This left the question as to whether the next run should be postponed until this work was complete or find alternative arrangements.

7.5.1 Appraisal of EMB Performance

The ultimate decision of whether to continue using the EMB machine was based on the appraisal of the machine's performance, from the data gathered from the load cell readings. Technical difficulties prevented the implementation of the load cells in the test-die until R_6 and, during this run, the button load cell, described in Chapter Six, failed, primarily due to excessive heat build up which distorted the plastic elements in the cell.

In contrast, the conditions within the die were well within the specifications for the Kistler load cell. Variables did change during R_6, whereas, in R_7, those variables were held constant. Figures 7.12 through 7.15 show four graphs generated from the Kistler load cell, located in the centre of the test-die.

The centre location for load cell readings was shown (in Chapter Six) to give the best indication of the machine's performance, as the forces recorded were a direct indication of the force exerted by the injection plunger. The maximum force the plunger exerted in any one shot was directly proportional to the efficiency of the pneumatic system and intensifier.

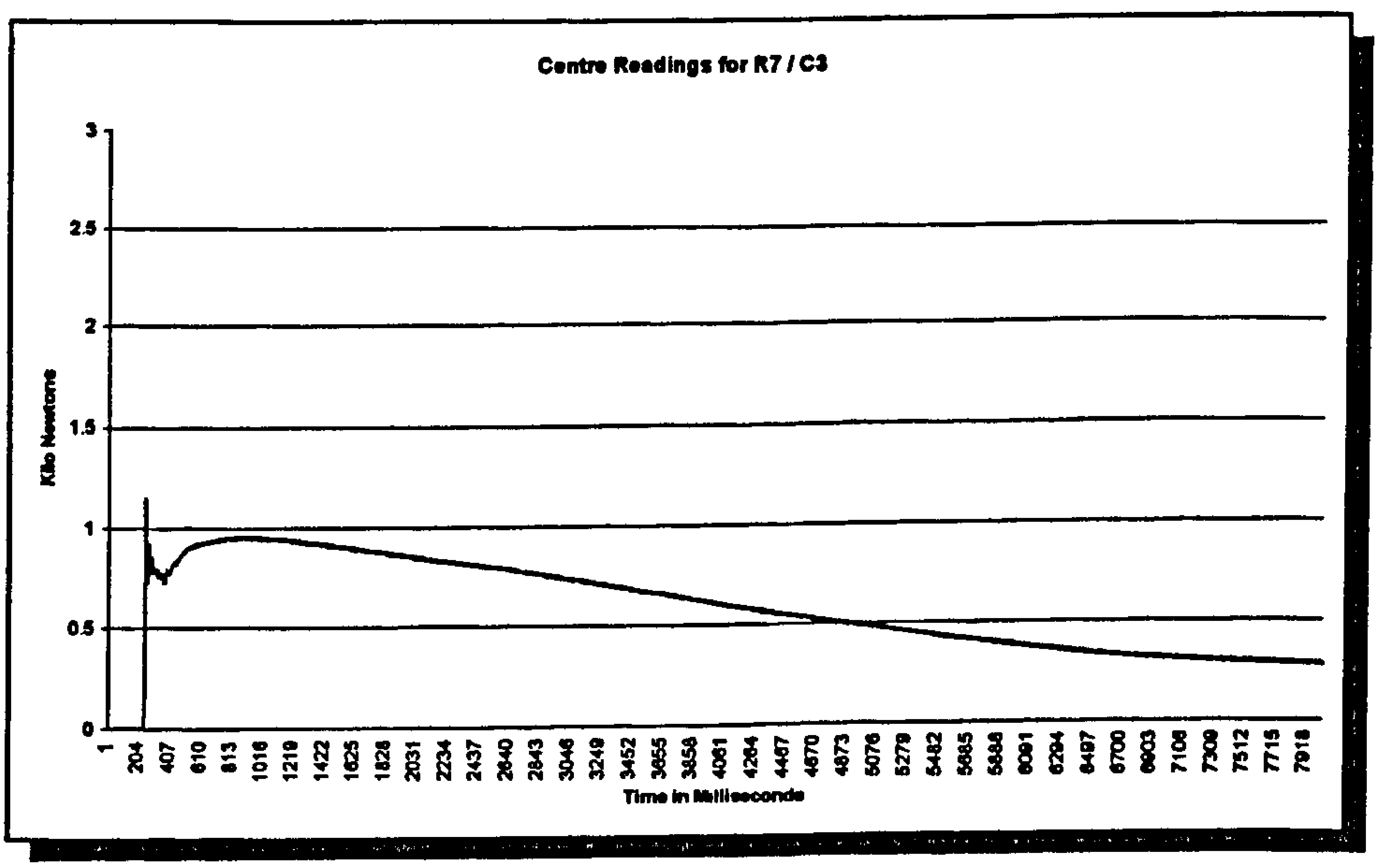


Figure 7.12 Load cell reading from R_7 C_2

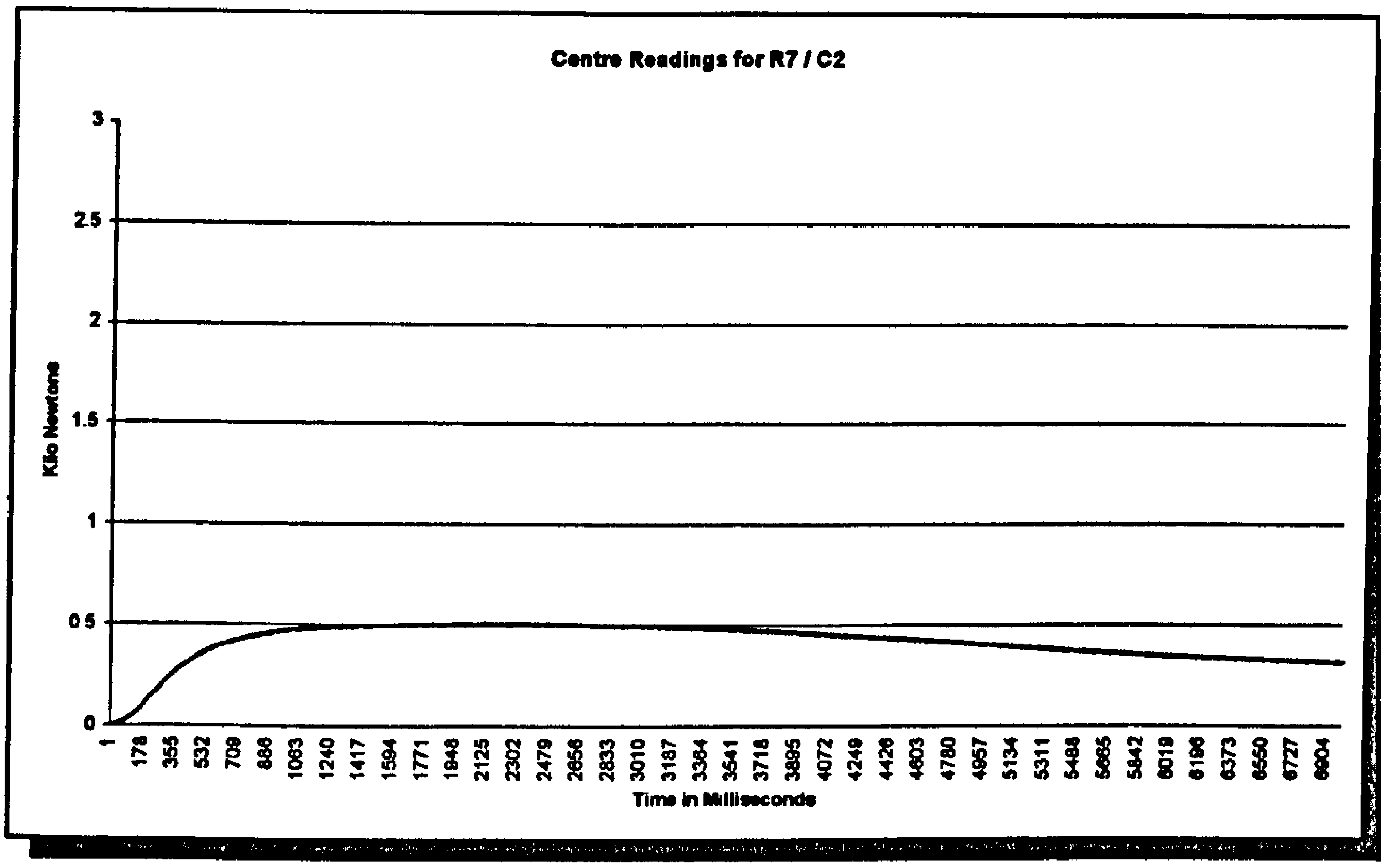


Figure 7.13 Load cell reading from R_7 C_3

At no time was the pressure, or speed, of injection altered during these castings. It was quite clear, however, that the load cell readings differed significantly. Careful calibration was performed, as well as temperature compensation, before each shot and it was surprising that any castings at all were produced from the EMB machine.

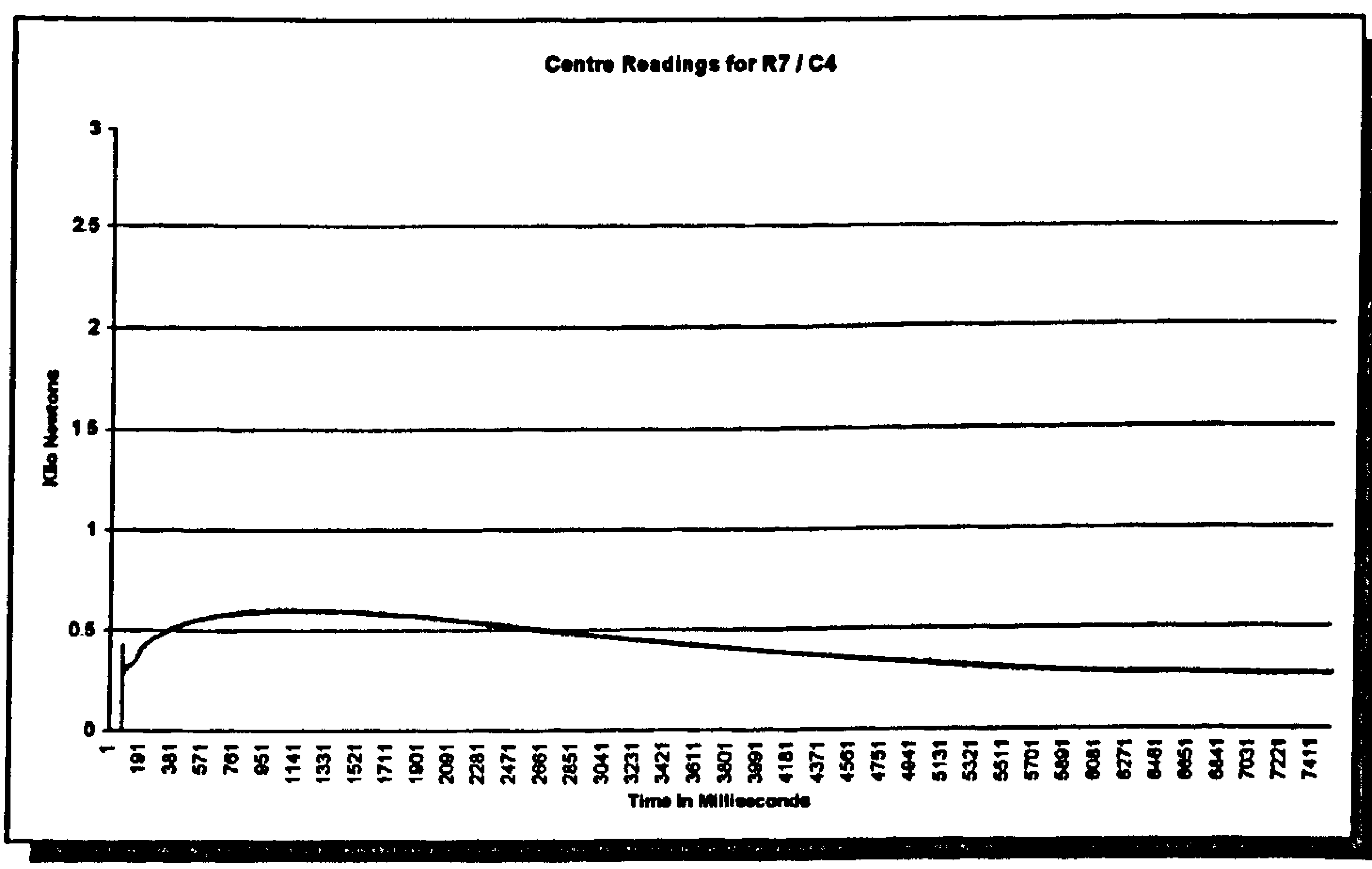


Figure 7.14 Load cell reading from R_7 C_4

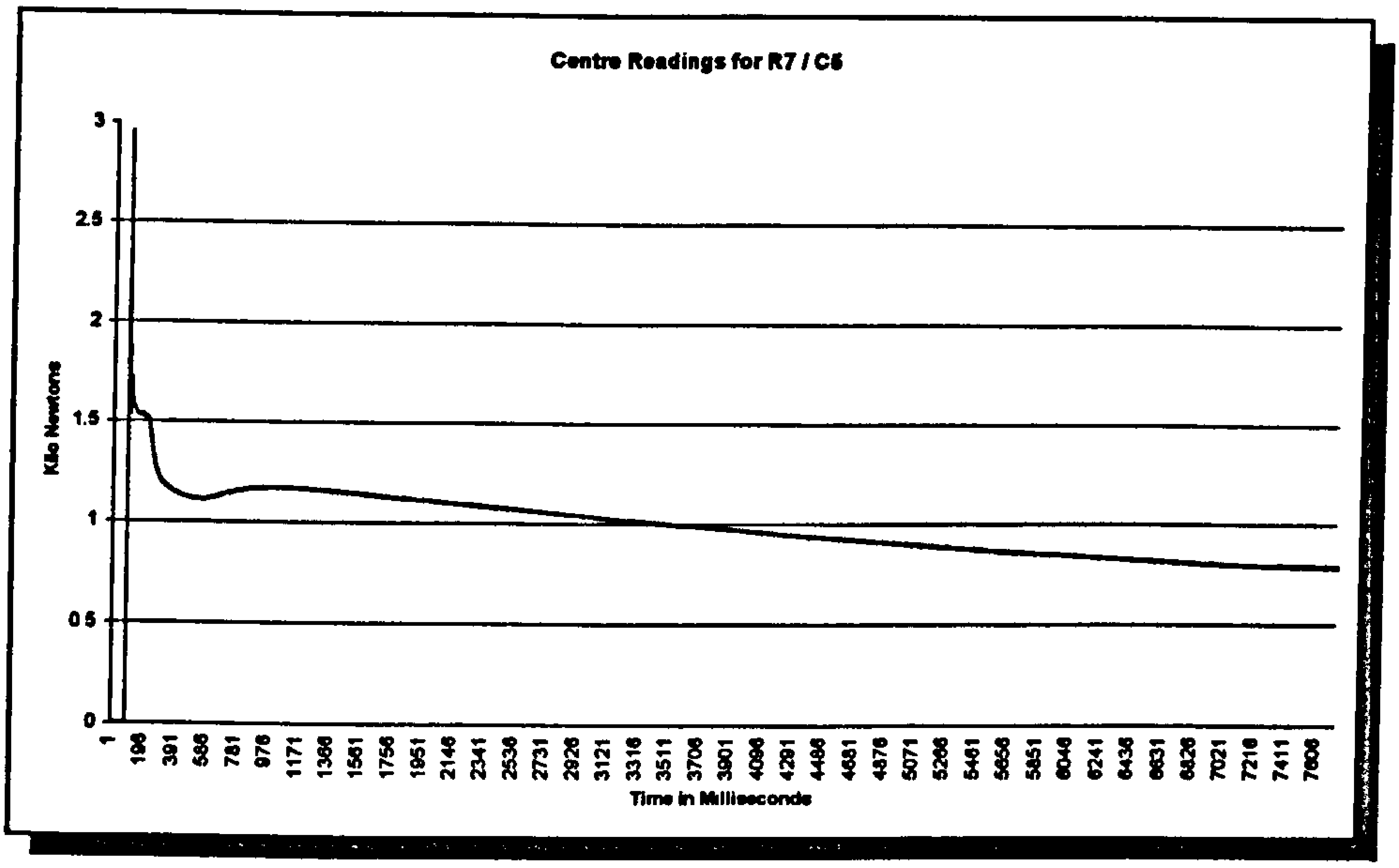


Figure 7.15 Load cell reading from R_7 C_5

The cause of this fluctuation was already known. During the early stages of the experiment, the air reservoir, which should supply a constant supply of pressurised air to the pneumatic system in the EMB machine, had exploded. A substitute reservoir was found but its capacity was significantly less than the original reservoir. In effect, the new reservoir could not supply a large enough volume of pressurised air to the EMB to ensure that each shot would be constant.

7.6 Summary

This experiment has proved that an un-bonded Laminate Tool designed specifically for one of the most arduous and challenging casting processes in use, can withstand the environment found in High Pressure Die-casting. This was the first implementation of a Rapid Tooling process into the die-casting industry. Further study was required as to how well such a tool would perform if un-bonded, as this, too, would allow multiple design iterations to be considered through the rapid exchange of laminate profiles within the tool. With correct clamping, it would be possible to test the validity of as many as three iterations in a day on the actual die-casting machinery which would be used in production, a concept which has never been an option to the designer.

This tool needed to be run-on to see if it could even be considered as a short-production run tool. What has not been discussed, so far, is the time that this tool took to construct, or its cost. To generate the CAD model and slice it, took an afternoons work, to submit the files to the laser profiler, nest each profile, cut and clean them, took two days. Assembly, took a further day, and the longest operation was the finishing of each insert to include gating, runners, ejectors, the parting line and mounting them in the bolsters. In a commercial workshop this could be done within the week. No finishing was applied to this tool and a further week would be required to complete this. This was not a production tool but a means to test a die design's validity, so tolerances did not need to be as fine. This means that a prototype Laminate Tool could be running within a fortnight and further iterations of the design would take just days.

As to the cost. The H13 sheet steel was commissioned especially for this research and so cost more than standard H13 billet 'weight for weight'. The cold rolled H13 came from Japan at £10/kg and the hot rolled H13 came from Austria at £5/kg. As it was, only four cold rolled sheets were required to generate every profile plus the extra profiles to exchange the laminate protrusions between runs. This came to around £250. The cost of profiling and cleaning came to £1000, the die-set a further £1000 (only required once), H13 stock for the clamping plates £200 and, machining and finishing, a further £2000 (40 hours at £50/hour). If a tool were to be used for short runs, it is almost certain that a lesser grade sheet steel could be used 'off-the-shelf', with a nitriding treatment to harden the surface. The total was, therefore, approximately £4,450.

Deformation was observed in the laminates which suggests there were limitations to an un-bonded Laminate Tool. What could not be established, at this point, was the laminate protrusion height at which ingress began to affect the performance of the tool. Analysis of the subsequent witness marks on the castings showed no correlation between the protrusion height and the size of witness mark recorded in the casting.

The evidence pointed to other variables at work, which were affecting ingress and these had to be identified. At this stage, the overriding variable was the EMB machine itself. For this reason, the next stage to this work was to run the test-die in the same set-up, on a more consistent machine.

Chapter 8: Experiment Two: To Analyse and Identify Deflection Variability in the Laminate Test-die

8.1 Introduction

The failure of the EMB die-casting machine meant that in order to identify the additional variables, it was first necessary to repeat the previous experiment on a more consistent high pressure die-casting machine and observe whether the same variability in the data was present.

8.2 Objectives

The objectives for Experiment Two were:

- To identify a new horizontal, cold chamber HPDC machine which could demonstrate consistent operational parameters.
- To modify and re-run the test-die in its set-up for Experiment One to ascertain if the variability, found in that experiment, was due to inconsistency in the EMB die-casting machine or if some other variable was at work.

8.3 Methodology

The procedure for Experiment Two was the same as in Experiment One outlined in

Chapter Seven. No changes were made in the method by which the castings were produced, sectioned and measured for witness marks.

Chapter Six highlighted the problems which were encountered in identifying a suitable die-casting machine. At the termination of Experiment One, a second search for a die-cast foundry which would allow access to a modern die-casting machine proved fruitless. At this stage, the author's PhD registration was transferred from the University of Nottingham to De Montfort University in Leicester. With this transfer, funds became available to consider the purchase of a new high pressure die-casting machine to house in the Department of Mechanical and Manufacturing Engineering at De Montfort University.

8.3.1 The Frech Die-casting Machine

The chosen die-casting machine had to meet the specifications for the EMB so that the laminate test-die could be mounted on the platens with minimal modifications. The machine chosen was a Frech 125 DAK horizontal cold-chamber machine. The specifications for this particular model are shown in Table 8.1.

Machine- type	**Frech DAK-125**
Locking Force	1250 kN
Opening Force	4700 kN
Closing stroke	340 kN
Ejector Force	80 kN
Ejector Stroke	90 mm
Die Height min-max	170-500 mm
Platen Size	620 x 620 mm
Space between tie bars	400 x 400 mm
Tie bar diameter	75 mm
Casting force max.	200 kN
Casting Stroke	310 mm
Injection plunger dia.	30, 40, 50, 60 mm

Casting Volume	260, 408, 584, 795 cm^3
Specific Injection pressure	1592, 1019, 707, 520 daN/cm^2
Casting Area	79, 123, 177, 240 cm^2
Max. Casting area	417 by 300 daN/cm^2
Working Pressure	105 bar
Dry cycle speed (DIN 24480)	800
Drive motor	15 kW
Weight of machine	6000 kg
Overall dimensions	5400x1380x2500mm

Table 8.1 Specifications for Frech 125 tonne HPDC machine

The Frech 125 DAK differed from the EMB machine in that it was completely hydraulic in operation, giving the unit much greater accuracy and repeatability of movement and force over pneumatic systems. Figure 8.1 shows the machine in place at De Montfort University.

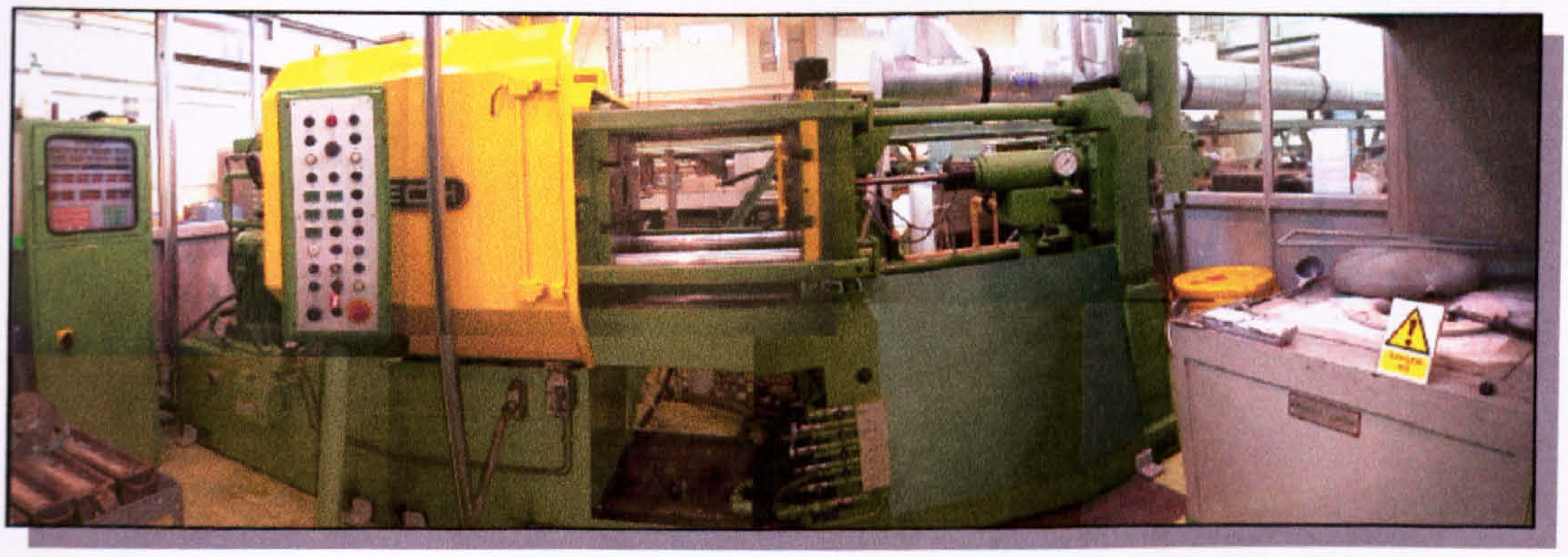


Figure 8.1 The Frech 125 DAK commissioned at De Montfort University

Based on the existing design of the laminate test-die, it was possible to calculate the set-up required for efficient operation. The performance diagram, in Figure 8.2, shows how the casting area, at the parting line ($93cm^2$), was translated into the required plunger diameter (in this case a 30mmØ injection plunger was used) and operating pressures for effective casting on the Frech 125 DAK.

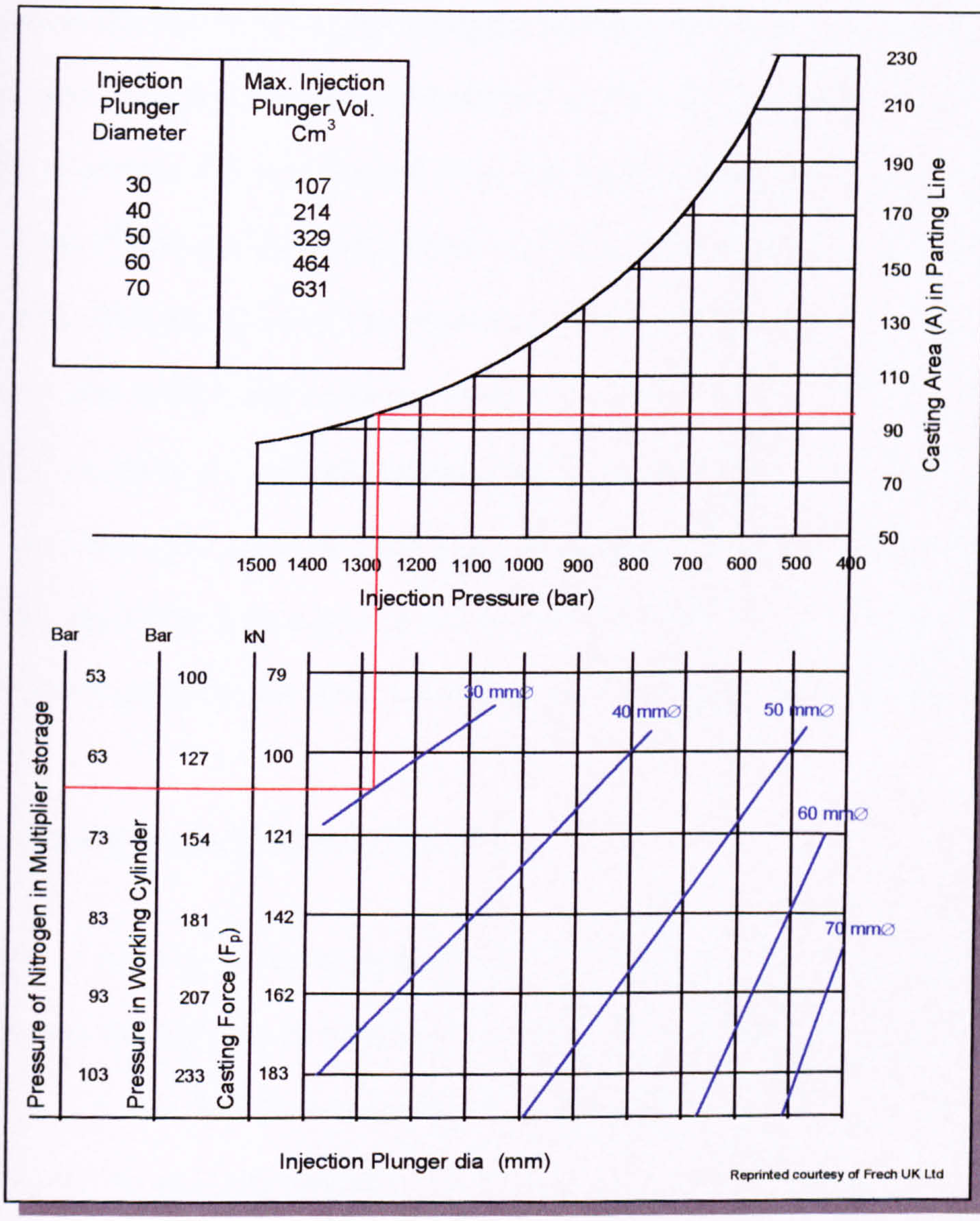


Figure 8.2 Performance Diagram for Frech 125 DAK

To ensure that the test-die could be run in its existing set-up, certain modifications had to be made to the die-set. The most important being the difference in the shot sleeve profile and the different ejector system on the Frech machine. Modifications to these are shown in the schematics in Appendix V (Figure 8 and 9).

The 125 DAK has 'real time' feedback for complete operating parameter control. A fully digital interface gathers data from pressure transducers and linear actuators throughout the machine (injection plunger, hydraulic system etc). The machine also comes with data logging hardware/software so the shot profile/performance can be monitored as each shot is performed. The data logging equipment allowed initiation of 1^{st}, 2^{nd} and 3^{rd} phase to be calculated and modified so that the machine performance was optimised. This also allowed for temperature compensation as the die heated up during a run, so that dwell times could be extended to ensure sufficient solidification before ejection. In addition, the Frech machine offered a completely automated shot cycle. An automated shot cycle removed many of the inconsistencies in the machine which were present in the EMB. Dies were supplied by Bosch GmbH to help in the setting up of the machine and complete runs of high quality castings were achieved on the first attempt.

8.3.2 Modifying the Molten LM24 alloy

The second major problem, encountered in the first experiment, was the failure of the furnace and the difficulty in holding the LM24 alloy at a constant temperature during operation. A new furnace was purchased from Ramsell Naber of the 'bail-out' type. The bail-out furnace was designed so that any temperature drop, caused through the removal of the lid to ladle alloy, was compensated for without affecting the quality of the alloy within. The furnace had a 40 litre capacity capable of offering an uninterrupted run of 100 castings before re-charging with new ingots.

One of the advantages of pressure die-casting is that any of the unused castings, or their runners can be re-melted in the furnace and re-cast. There was a limit to how much 'scrap' could be used in the furnace at any one time, due to the impurities that the alloy picks up from the release agent in the die-cavity. In these experiments, a lot of scrap was generated as the castings were sectioned and only a small part was measured. The re-melted alloy was prone to grain enlargement and embrittlement through the absorption of hydrogen from the surrounding atmosphere, leading to poor casting quality and reduced fluidity which could affect deflection. To ensure that the grain structure remained as consistent as the virgin LM24 ingot, from one run to the next, it was necessary to modify the alloy whilst in the furnace.

Two methods chosen to overcome embrittlement. The first was to 'bubble' pure nitrogen through the melt before each run. This drove off any reactive gasses present in the melt and the surrounding furnace chamber which would otherwise react with the molten LM24.

The second approach was to sprinkle sodium fluoride powder onto the surface of the melt. Sodium fluoride served two purposes, it aids in the separation of dross from the melt which either sinks to the base of the crucible or floats to the surface, forming an impermeable (to hydrogen) crust. Also the sodium reacts with the aluminium alloy to form a fine grain structure during solidification and improves fluidity during injection.

8.4 Procedure

No modifications were required to the laminate inserts, except for a new set of laminate protrusions for each ramp feature. Test runs on the laminate die were performed to set appropriate operating parameters and the shot parameters are shown in Table 8.2.

Machine- type	Frech DAK-125
Max. piston velocity(1st phase)	0.15[m/s]
Start 2nd phase after	140[mm]
Start 3rd phase after	270[mm]
Speed 1st phase:	0.07[m/s]
Speed 2nd phase:	0.75 & 2.0[m/s]
Shot sleeve volume	7.06[cm^2]
Max. machine (hydraulic) pressure	300[bar]
System pressure for Injection	105[bar]
Intensifier plunger ratio	130/80[mm]
Plunger extension	315[mm]
Alloy	LM24
Pouring temperature	720[°C]
Die coating material	Klubertec HP1412
Initial temperature of the die	180[°C]
Ingate velocity	2.48[m/s]
Shot weight:	250[g]
Shot chamber filling	60[%]
Casting weight (without gating)	120[g]
Casting area at parting line	91[cm^2]
Actual cycle time (approx.)	260.0[s]
Die opens after	5.0[s]
Closing time	4.0[s]
Ejector return delay	2.5[s]
Plunger return delay	1.5[s]

Table 8.2 Shot parameters for Experiment Two

Two 2nd phase injection speeds were utilised in this set-up. The slower injection speed of 0.75m/s was used to 'run the die in' for the first two or three shots, until a uniform heat distribution was achieved throughout the die cavity. At this point, the injection speed was increased to 2m/s. The shot profiles for these two set-ups are shown in Figure 8.3 and 8.4.

In both Figures 8.3 and 8.4, there are two graphs represented for each profile. The upper line denotes injection velocity (v) and, the lower, the pressure applied (p) to the alloy during the three phases of injection. The vertical lines (green) on the graphs represent the point at which each phase is initiated.

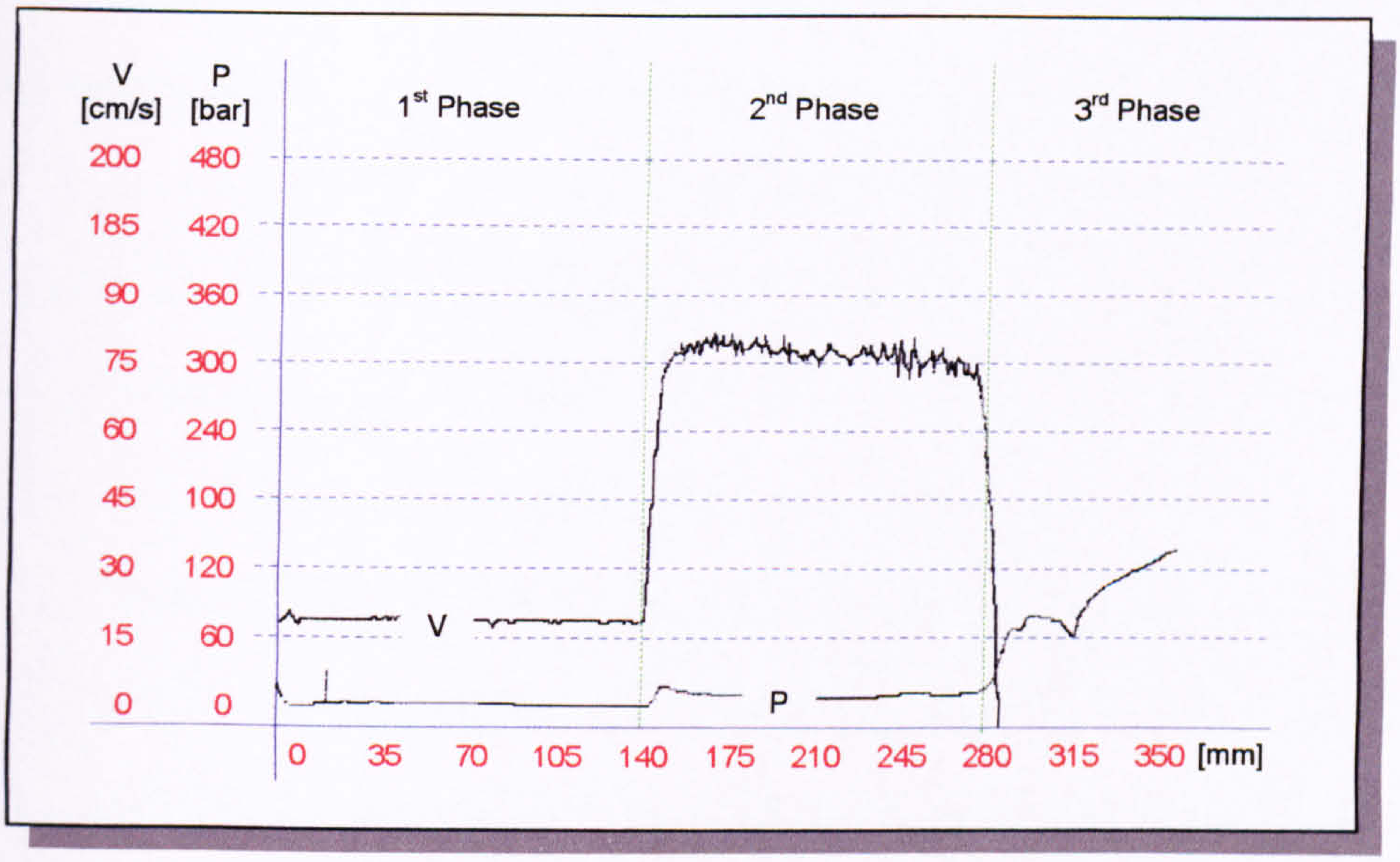


Figure 8.3 Shot Profile at 0.75m/s injection speed

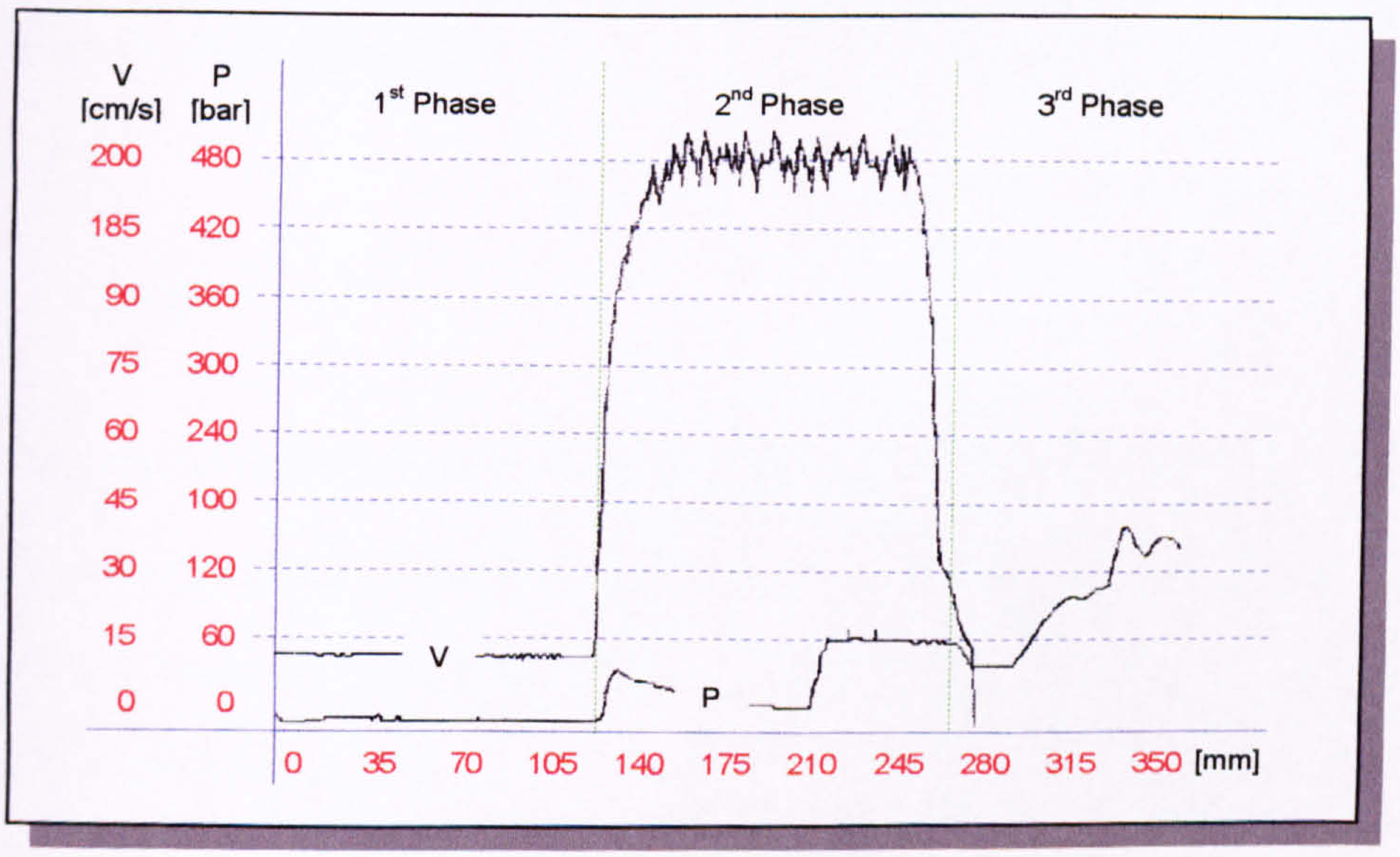


Figure 8.4 Shot Profile at 2m/s injection speed

As with Experiment One, a complete run of ten castings (R_8) were taken and coded with the prefix C_{1-10}, which denotes the order that the castings came off the machine. Each casting was then sectioned, as before, to allow measurement of any witness mark present as a direct indication of the magnitude of deflection experienced by that particular laminate protrusion.

A final modification, over the first experiment, was to use one of the standard release agents discussed in Chapter Seven. This agent was a polysiloxane solution mixed with water at a ratio of 1:80. Concerns had been expressed regarding the detrimental environmental consequences of using the colloidal graphite release agent and the fumes from the small amount of synthetic oil burning off the die surface during casting. Polysiloxane release agents (manufactured by Klubertec Ltd) produce a very clean casting, almost no noxious fumes and are applied to the die surface as a spray between shots. This high water content in the release agent was also useful for die cooling as no cooling system was in place in the test-die. As discussed in Chapter Seven, there was an increased chance that the castings may seize in the die due to the untreated die surface in the laminate test-die.

8.5 Results

The Polysiloxane release agent proved less forgiving than the graphite, as it was critical to remember to apply it liberally between shots. This may sound obvious, but, when operating a die-casting machine, there are many different elements to monitor. A complete set of ten castings were produced, however, and the resultant castings were very clean compared to the castings in Experiment One. They also showed excellent homogeneity compered to the earlier castings, which suffered from porosity. Figure 8.5 shows one such casting.

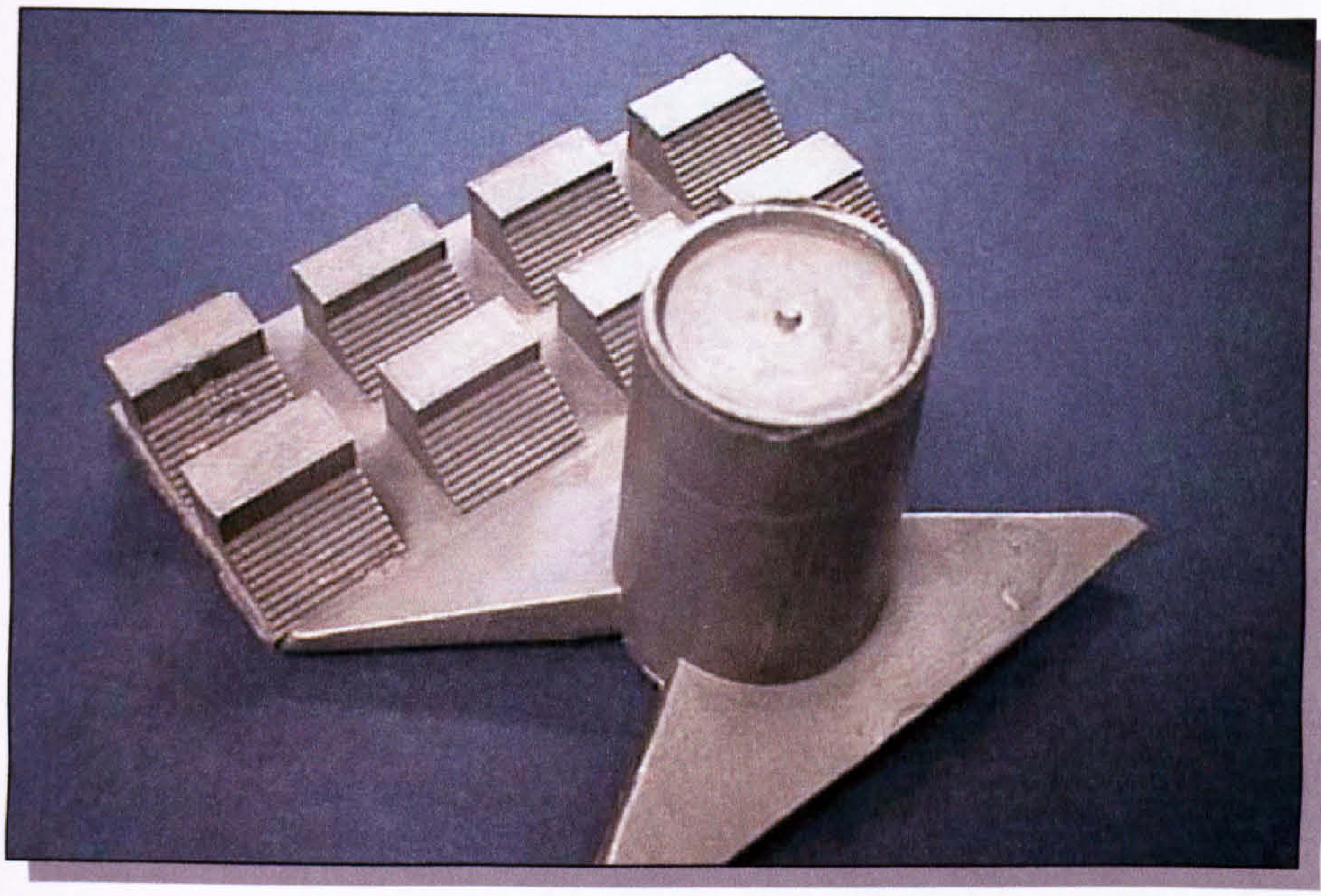


Figure 8.5 Typical casting from the Frech 125 DAK

The ten castings ($C_{1\text{-}10}$) were sectioned, as in Experiment One, and measurements were taken of any witness marks on the castings. The measurements are shown in Table 8.3.

Casting Number	6.00 mm Up-stand 'A'	4.00 mm Up-stand 'B'	2.00 mm Up-stand 'C'	1.50 mm Up-stand 'D'
C_1	0	0.05	0.05	0.05
C_2	0	0	0	0.15
C_3	0	0	0	0.07
C_4	0	0	0.05	0.06
C_5	0	0.06	0.05	0.05
C_6	0	0	0.05	0
C_7	0	0	0.06	0.05
C_8	0	0	0.1	0.06
C_9	0	0	0	0.06
C_{10}	0	0	0.09	0.07
Mean	**0**	**0.011**	**0.045**	**0.062**

Casting Number	5.00 mm Up-stand 'E'	3.00 mm Up-stand 'F'	1.0 mm Up-stand 'G'	0.25 mm Up-stand 'H'
C_1	0	0	0.07	0
C_2	0	0.1	0	0
C_3	0	0.1	0	0.05
C_4	0	0	0.1	0
C_5	0	0	0.07	0
C_6	0	0.1	0.09	0.05
C_7	0	0	0.08	0
C_8	0	0	0.11	0
C_9	0	0	0	0.06
C_{10}	0	0.05	0.1	0.05
Mean	**0**	**0.035**	**0.062**	**0.021**

Table 8.3 Mean Ingress of ten castings from R_8

The columns show the location of each up-stand within the test-die, as well as the amount of protrusion above the ramp on each up-stand feature along with the ingress measurement in millimetres. From the data, a graph was plotted in the same way as for Experiment One, as shown in Figure 8.8.

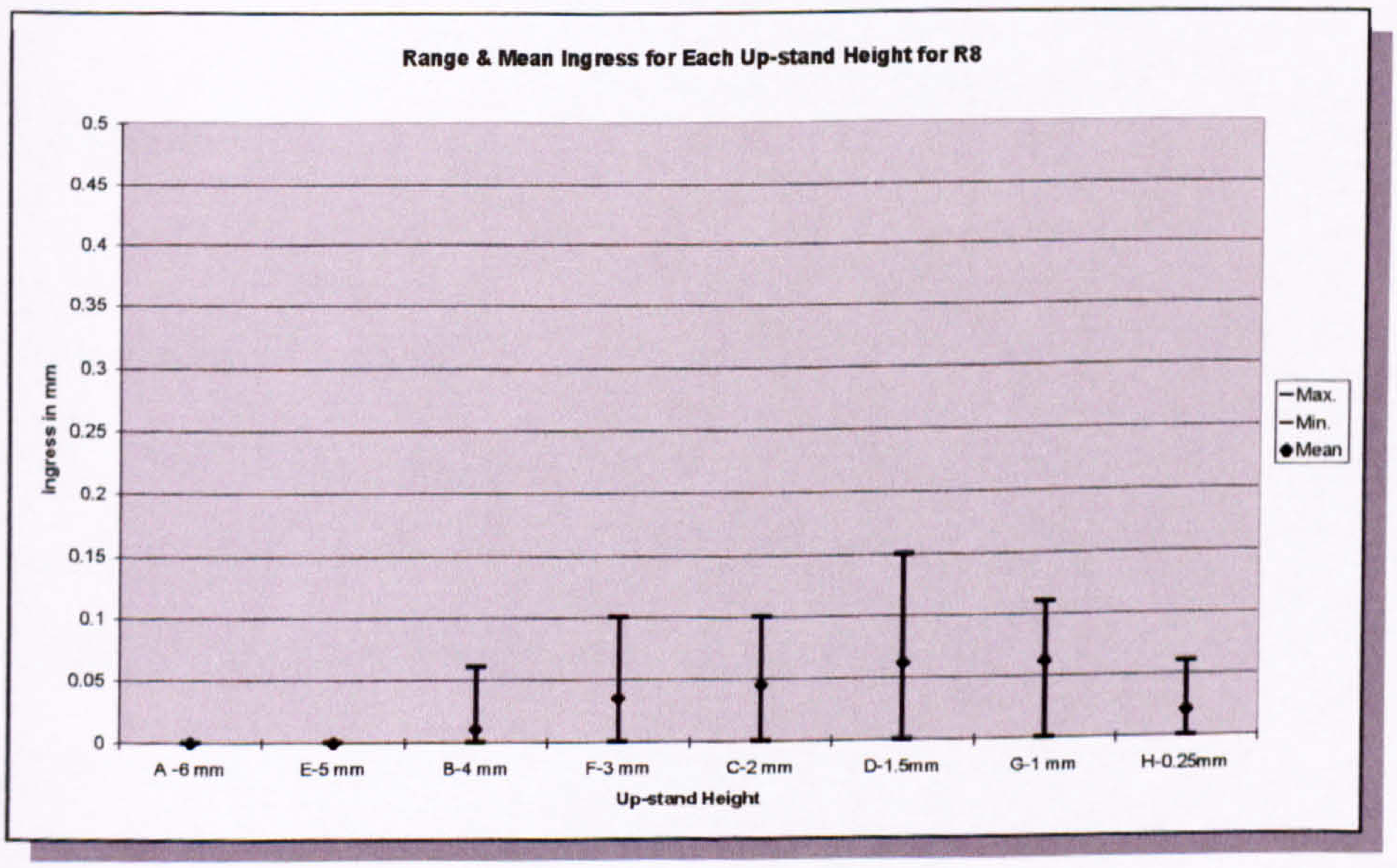


Figure 8.6 Mean ingress for ten castings from R_8

There are three measurands shown for each ramp feature which relate to the maximum and minimum width of the ten witness marks of each set of castings, and the mean width for each ramp feature (due to deflection and ingress). The graph indicated a skewed curve of ingress over the range of up-stand features but also showed that ingress increased as the laminate protrusion height decreased. This was almost the inverse of what was expected if the laminates were deflecting through the action of molten alloy on each laminate protrusion and confirmed the findings from Experiment One, i.e. deflection was being influenced by variables other than the laminate's protrusion height.

The Frech die-casting machine produced better quality. Even with the new machine, variability of ingress was still evident. This implied that the magnitude of deflection experienced by a laminate protrusion was, possibly due to some other variables, other than the laminates protrusion height above each ramp feature.

8.6 Discussion

The graph shown in Figure 8.8, and the data in Table 8.3, gave some clues to the identity of the overriding variable, which had not been accounted for up to this stage in the research. Each ramp feature (A through H) on the graph related closely to that feature's physical location in the test-die. To aid visualisation of each feature's location in the test-die, the CAD model in Chapter Seven has been duplicated, as shown in Figure 8.9.

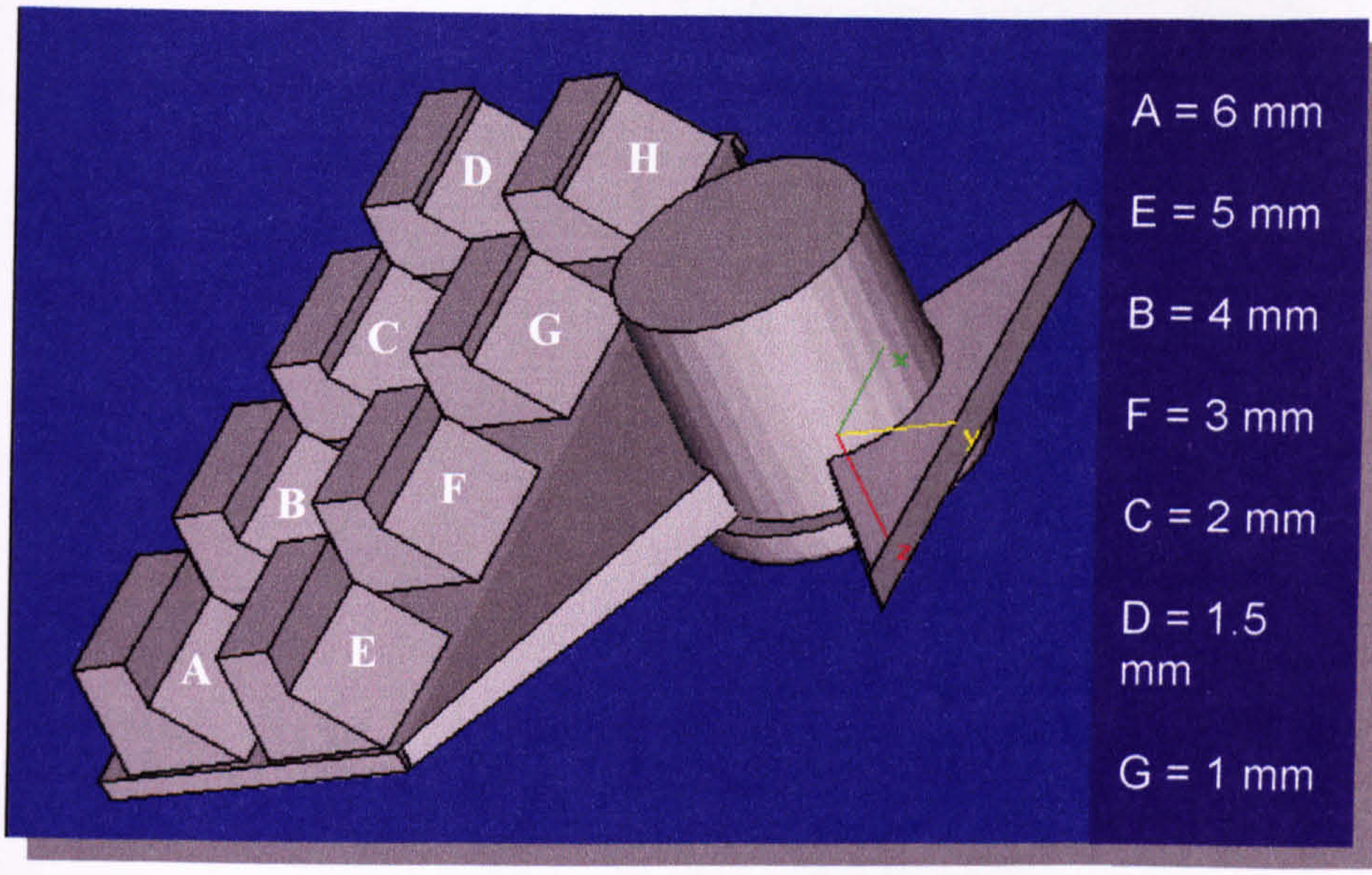


Figure 8.7 Location of each ramp feature, A through H, on the casting

Ramp's A and E were located on the far left of the test-die (here shown on the casting), ramps B and F and C and G were next, with ramps D and H being located on the far right. With this in mind, it would appear that the magnitude of deflection exerted on an individual laminate was greatest in the centre of the die.

8.6.1 Hypothesis for Variability in the Deflection Measurements

In identifying the additional variable the following hypothesis considered:

The magnitude of deflection experienced by an individual laminate protrusion within the test-die is dictated more by the laminate's location in respect to the inlet gate than its protrusion height.

This was a difficult question to answer, as it was impossible to see inside the die during injection. The only way to prove or disprove the hypothesis was to identify all possible explanations and use reasoned argument (logic) to leave just one outcome. As it was there were just two:

- The magnitude of deflection of a laminate was being influenced by a partial 'backflow'.

- The magnitude of deflection of a laminate was being influenced by its location in respect to the inlet gate.

The second explanation is reasonably self-explanatory, the first is not. Backflow is a known phenomenon identified by Miller *et al* (1996). The principle of backflow centres on the behaviour of molten alloy as it passes through different gate designs. The condition occurs where an inlet gate has been designed too narrow (in plan view). The effect is to form a jet of molten alloy that surges up the centre of cavity and returns back on itself down the sides. This effect is shown in Figure 8.8.

In Figure 8.10 the inlet gate is restricted to the width of the material entering the die cavity and is relatively narrow. This forms the jet (stage one), mentioned previously, which travels up the length of the cavity, splits (stage two), returns down the sides of the cavity (stage three) before joining the flow of material still passing through the inlet gate (stage four).

This motion sets up a large amount of turbulence within the molten alloy, particularly as all die cavities have some form of obstruction to that flow within the design. The swirling (turbulence) also creates excessive oxides and can trap gasses in the centre of the solidifying alloy with detrimental effects on the quality of the casting.

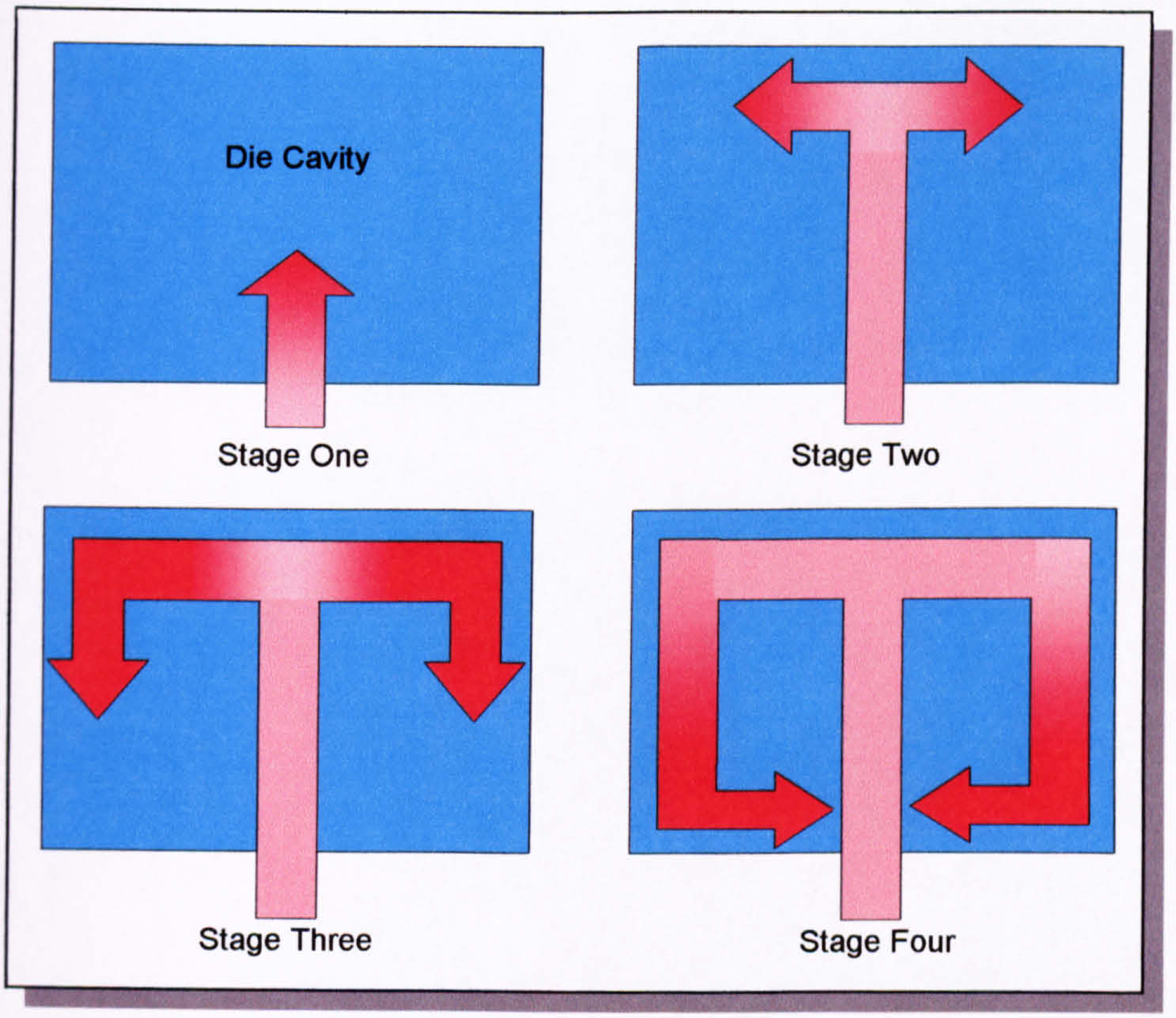


Figure 8.8 The effect of 'backflow' in the die cavity

If this condition were present in the laminate test-die the result would have been that deflection would be measurable on the central laminates and not on those at the sides of the die. This is because molten alloy would be flowing in the opposite direction at the sides of the die-cavity leading to no deflection on these features.

This could not happening, however, in the laminate test-die, as some ingress had been recorded on the laminates at the sides of the die cavity. Therefore, 'pure' backflow was not present in the test-die. However, the assumption was for a narrow inlet gate and not for the fanned inlet gate present in the test-die. Under ideal conditions, the laminate test-die would fill, as shown in Figure 8.9.

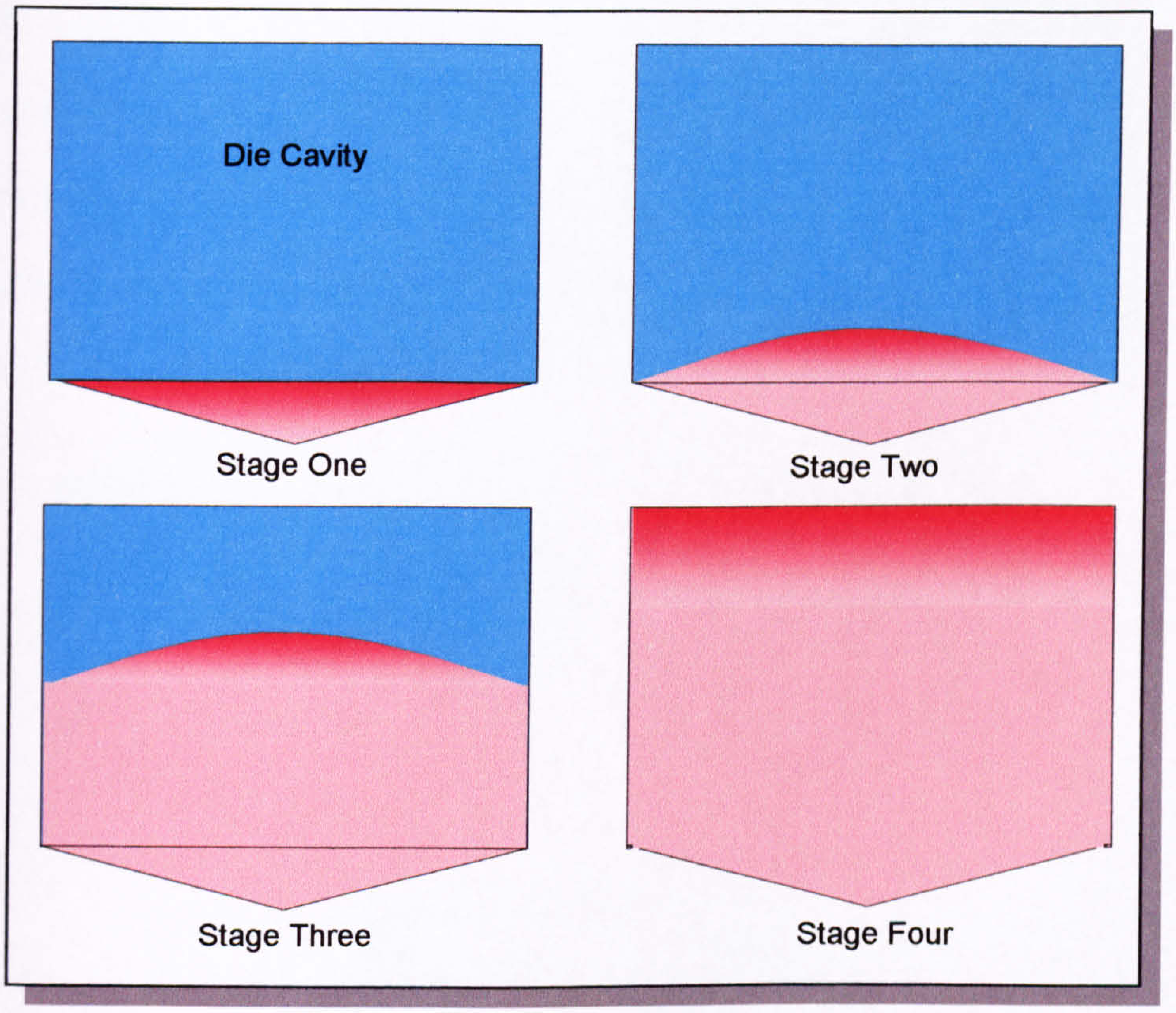


Figure 8.9 Ideal filling behaviour for laminate test-die

As the alloy enters the die, it progresses evenly through the die-cavity as a uniform 'flow front' passing over each laminate ramp feature until the alloy reached the rear wall of the cavity.

The question, therefore, was whether 'partial' backflow conditions were occurring with the fan gate in the test-die. An error in the cross-sectional depth, or design, of the inlet gate could have been causing the alloy to flow up through the centre of the die and then around the rear of the die. What may differ from the model by Miller *et al* (1996) was that alloy could have been forming a peak flow (or partial jet) through the centre of the die cavity as shown in Figure 8.10.

As the alloy leaves the inlet gate (stage one), the majority of the flow travels up the centre of the die cavity. The flow front strikes the rear of the die cavity (stage two) and begins to spread around the rear of ramp features A and D (in the rear corners of the cavity), before meeting the slower moving material still passing over ramps E and H along the sides of the cavity.

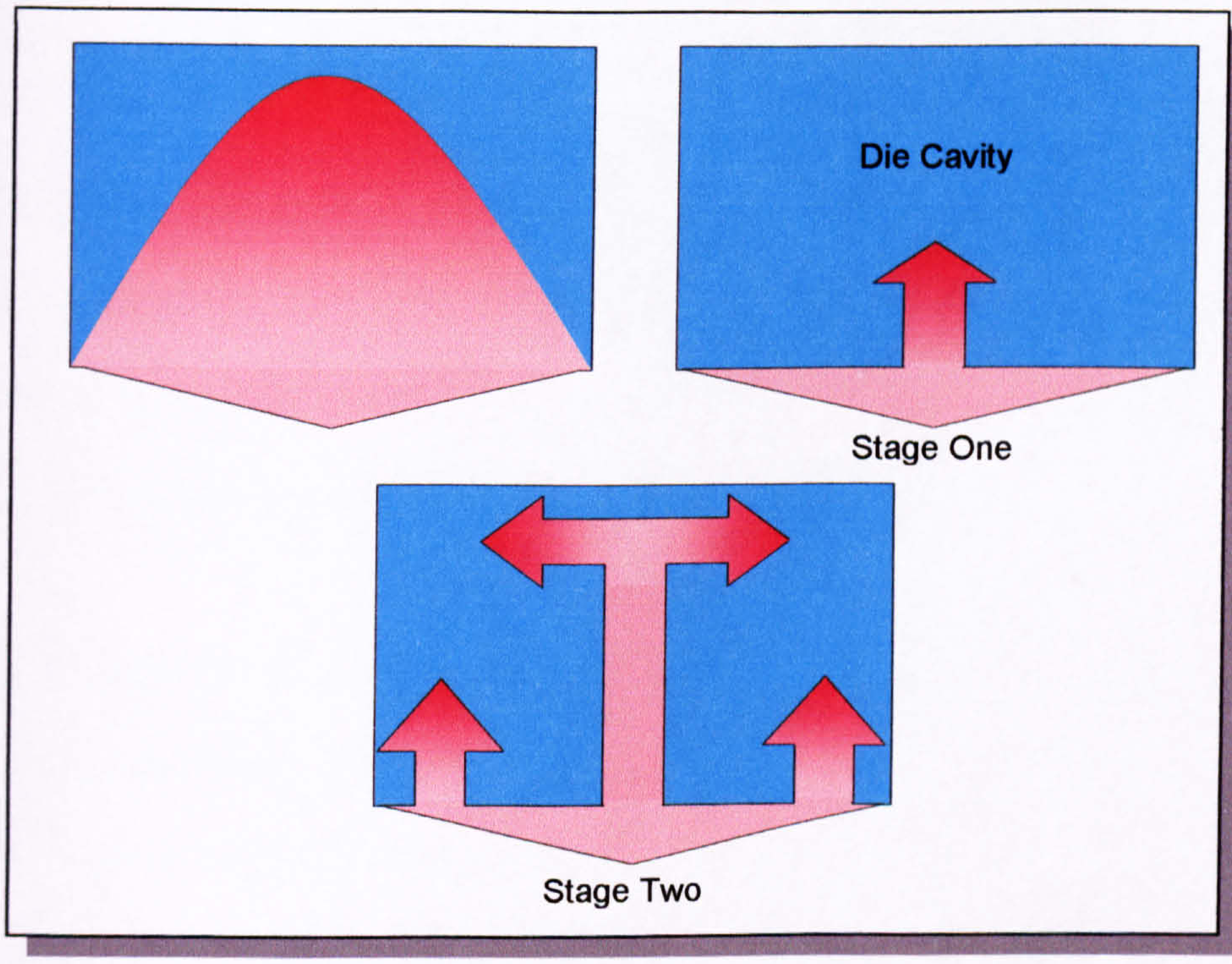


Figure 8.10 Possible effects of uneven flow through the inlet gate on test-die

How far the partial jet would travel, around the rear of the die cavity, would be dictated by how far the alloy passing up the sides of the cavity had travelled before the two flow fronts met and the flow was arrested. If this were happening in the test-die, then there would be a partial equalisation of the force exerted on the laminate protrusions at the sides of the cavity, resulting in a reduction in deflection and the ingress measurements on these features as indicated in the graph.

If this were the case then the variability hypothesis could be rejected as the conditions were based on backflow and not location. The consequence of this would be to ignore the measurements taken from those laminates at the sides of the die cavity. This could only be verified by measuring the depth of the inlet gate, where it met the die cavity, to see if it varied enough to cause partial backflow conditions.

8.6.2 Measurement of the Inlet Gate

In Chapter Six the design of the inlet gate was described. The objective of this design being to spread the flow of the molten alloy across the width of the die cavity so that, theoretically, it would travel uniformly up the die cavity, passing, with equal force, over each laminate protrusion in the die.

Uniform spread of the alloy across the inlet gate was only possible if the gate had been machined, accurately, into the cover die during its construction. If the depth of the gate were deeper in the centre then a larger quantity of alloy would pass through it at this point, potentially forming a 'partial' jet of molten alloy, leading to backflow conditions. The cross-sectional depth of the inlet gate, at the point it met the die cavity, was measured. The dimensions of the inlet gate and the location of each measurement of the test-die are shown in Figure 8.11.

Measurement was by co-ordinate measuring machine (CMM) and was taken from both ends of the gate at 5mm intervals. The measurements indicated that the inlet gate was wider at the side where material passed over ramps C, G, D and H. This indicated that molten material may have been flowing faster at this end of the inlet gate than the other and not at the centre of the gate as initially suspected.

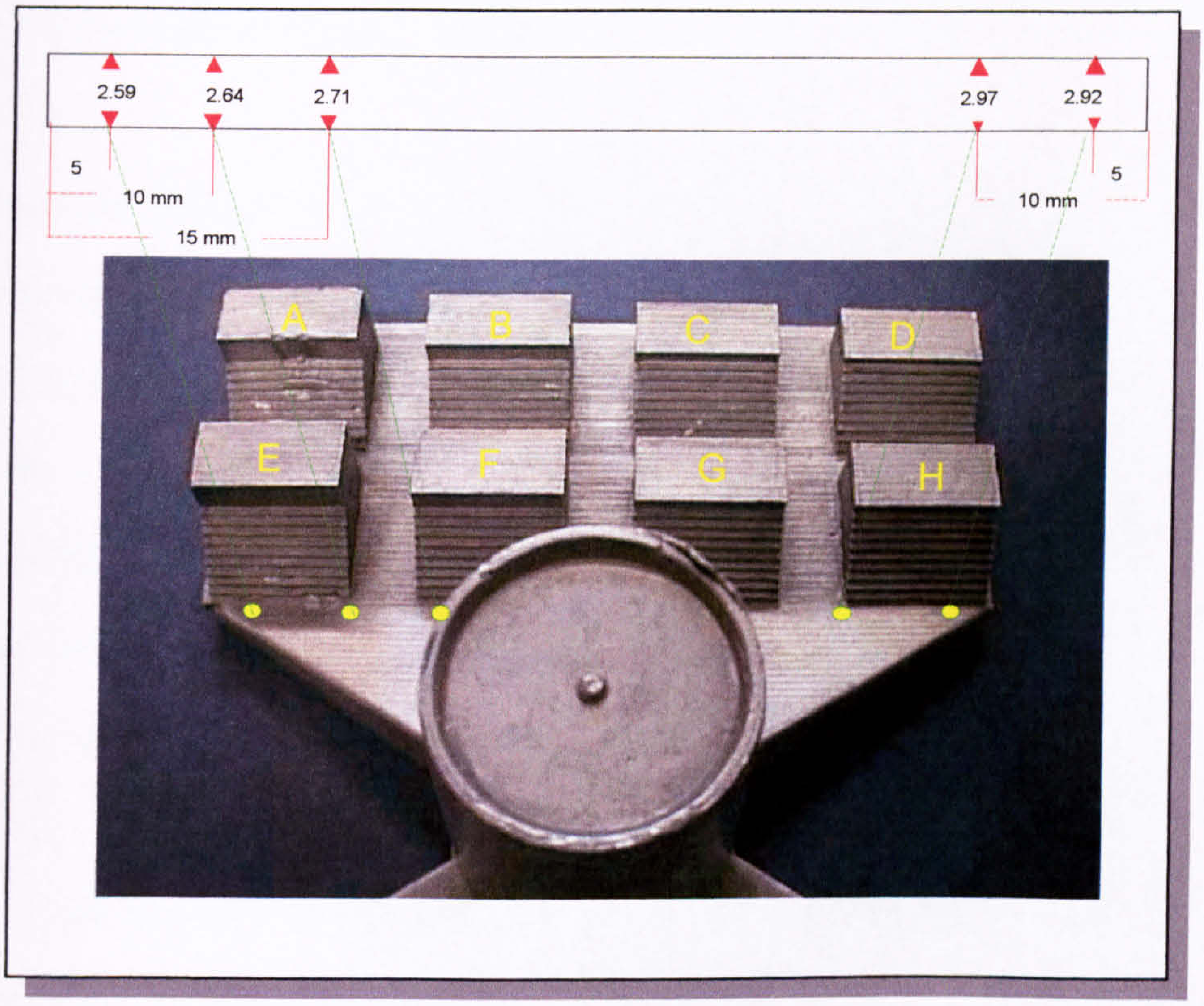


Figure 8.11 Casting showing location of measurement points

If alloy was leaving the gate one side faster than the other, then the alloy would be effectively swirling around the inside of the die cavity. This would register as large deflection measurements on those laminates on the right side of the die cavity and none on those laminates on the left side of the die-cavity. The conclusion, at this stage, was that 'backflow' conditions were not present and, therefore, location variability was the likely cause. To prove this conjecture it was decided to run a series of simulations of the flow within the die cavity.

8.6.3 Simulation of Flow within the Die Cavity

During the initial stages of the design process for the test-die, the use of flow simulation software was considered, but rejected, as part of the design verification process for the laminate test-die. This was not possible, the main reason being that the technology had not been developed sufficiently at that time.

Commercial versions of Computational Fluid Dynamics packages for HPDC began development in 1991 (Mahaney and Kim, 1996), the first being launched in 1993 (EKK Ltd). Over the last decade the increase in computing power has enabled this technology to make a presence in the industry. To date, these systems are expensive (currently ranging from £3,000 to £10,000), but approaches were made to Magmasoft Ltd, who kindly consented to run a simulation for the test-die in an attempt to identify whether location variability was affecting the experimental data.

Magmasoft, like most of the 'high-end' HPDC-CFD software packages (EKK, Flow-3D, Procast, Castflow and Technalysis), use the Finite Element method (FEM) to generate and identify the relevant elements and nodes required to perform a complete simulation of the flow of molten alloy through the die cavity. This is opposed to the low-end and now outdated approach, of defining the shape of the cavity through the Finite Difference method (FDM) which uses a less powerful algorithm (and thus saves on time to make the calculation) by defining the 3D volume as discrete cells or blocks (Caulk, 1996).

FEM is rapidly becoming the industry standard, as modern processors can now deal with the relatively massive calculations required. In addition, the increasing use of Solid CAD modelling provides an excellent platform on which to generate the required mesh used in the calculations (the .STL format for tessellation of a CAD model can be used directly by many FEM packages).

The use of computer simulation for HPDC applications is divided into three distinct areas (Mahaney and Kim, 1996):

- Solidification analysis
- Stress analysis
- Filling or Flow analysis

Solidification analysis includes thermal distribution analysis and is used to assess the distribution and affect that the heat, in the molten alloy entering the die cavity, will have on the individual die elements. The algorithms used in die-casting simulation do not differ from those used in other applications, such as injection moulding (Moldflow Ltd, ALGOR), as the boundary conditions for different moulding/casting materials are fairly constant.

Stress analysis has become a classic use for the FEM approach for many different applications, besides HPDC, whereby the affect of forces (load, heat, pressure) can be studied to observe their affects on certain elements of a mould, die, beam, etc. There are limitations on how many elements, or nodes, can be calculated simultaneously in a simulation. For example, it is difficult to monitor, efficiently, the stress imparted on a complete die cavity from the alloy being forced into it.

Popular FEM packages, such as ALGOR, can only analyse, in detail, a small area of a die the size of the laminate test-die. The detail and, therefore, the accuracy of these calculations are directly dependant on the number of elements which are identified (discretised). Reducing the resolution (number of nodes and elements used) of the analysis would allow the entire test-die to be appraised but the accuracy of that simulation would be questionable.

Of the three approaches, filling and flow simulation is the most calculation intensive. To analyse the effectiveness of a die design, by simulating the way the die fills during each shot, requires the use of Navier-Stokes equations. The analysis of fluid flow, though technically a branch of FEM, has become increasingly associated with Computational Fluid Dynamics (CFD) and is now a field of simulation commonly separate from thermal and stress analysis. Specifically, fluid flow analysis using Navier-Stokes, is the study of a fluid's viscosity and its interaction with the material constraining it (Wendt, 1992).

Within HPDC, the key to accurate simulation of the flow of a pressurised molten alloy through a die cavity is dependent on the accurate, numerical representation of the boundary conditions affecting that flow. In Chapter Four, the specific problem of establishing the viscosity of molten alloys was discussed due to the affects of aggressive interaction of gasses within the die cavity and the flow front of the molten alloy passing through it. To this end, it was explained that the term 'fluidity' is used to describe the behaviour of a molten alloy, which takes into account this interaction and, therefore, the difference between molten alloys and, say, thermoplastics whose viscosity behaves in a linear manner dependant on its temperature.

Identifying the boundary conditions, specific to HPDC (change in fluidity, dissipation of heat into different die materials, friction and, currently, turbulence), has been the background to extensive research over the last decade (Caulk, 1996). In line with this, Magmasoft's software, as well as the other vendors mentioned, utilises:

- Automatic and semi-automatic mesh generation. Multi-region 3D mesh generation is essential to model the die (stress and thermal analysis FEM systems only model the casting) to take into account cooling lines, die inserts etc.

- Full Navier-Stokes calculations to simulate the entire casting and its effectiveness for any given design.

- Flow-front or 'free surface tracking' algorithms to take into account the changing viscosity of the alloy entering the die cavity.

- Cyclic analysis to take into account the changes in die behaviour over more than one shot.

In the example of the laminate test-die, a total of 30 parameters were entered into the model which describe, exactly, the performance of the Frech die-casting machine and the LM24 die-casting alloy. The model itself was generated from the original 3D-CAD model of the test-die. A total of 1,994,106 elements were defined on the model and the simulation was run over 24 hours on a high-end UNIX workstation. It should be remembered that the CAD model of the inlet gate was perfectly uniform and was not representative of the actual gate dimensions measured in the previous section. Figure 8.12 shows fourteen 'x-ray' frames from the entire sequence of the casting as it fills.

The sequence was indexed by time (in seconds), showing temperature variations throughout the casting

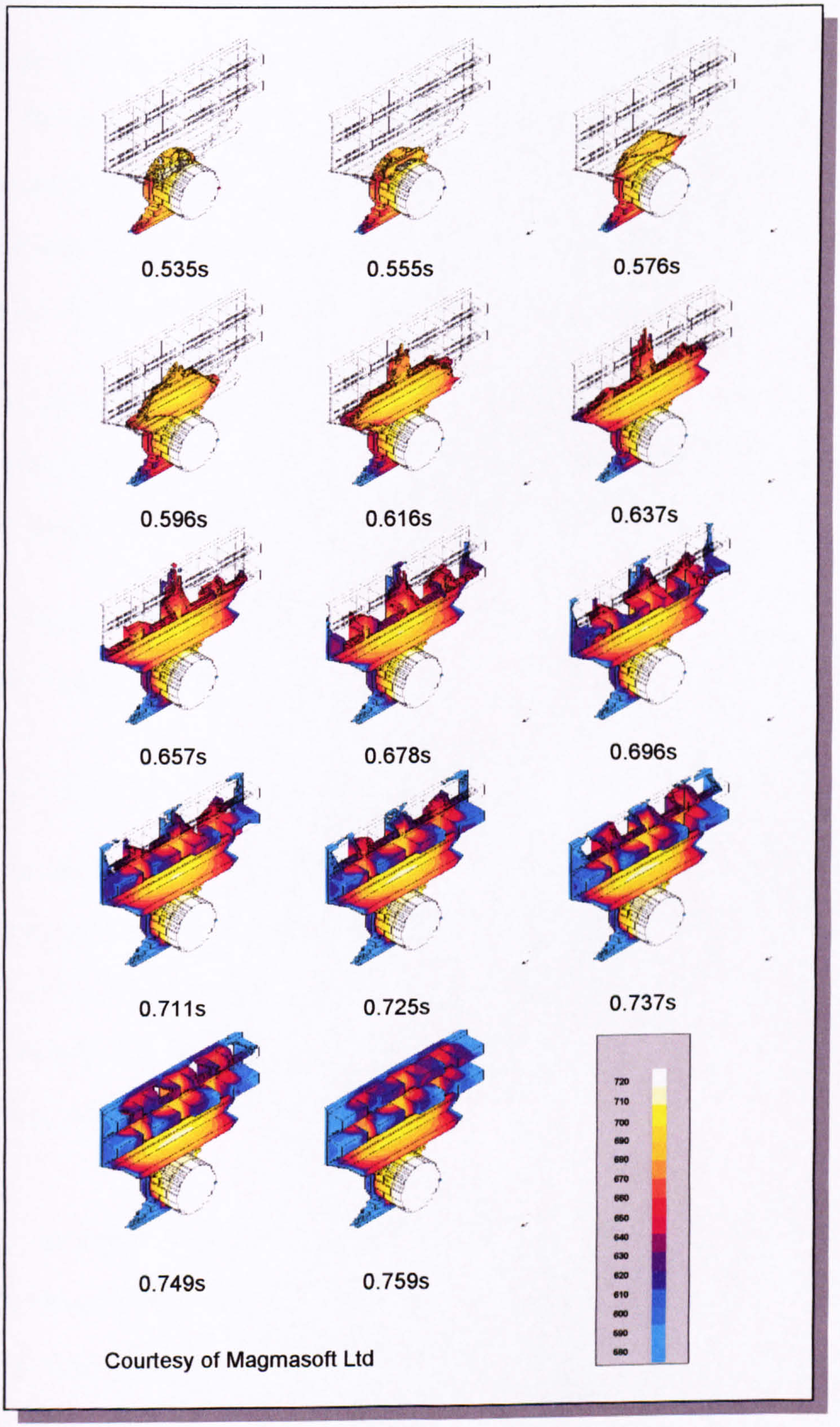


Figure 8.12 Sample of 14 frames from the CFD simulation

For this simulation, a 'structured cartesian mesh' was used to discretise the model. Nodal points were assigned to each 'cube' element with LM24 flowing from node to node. The size of each cube element was defined by the detail required at that location in the model and results in the 'blockiness', which can be seen on the injection sleeve element and inlet gate where the nodal volumes were greater (less detail required). From this analysis the following observations were made:

- The flow of alloy through the inlet gate was balanced but was not spreading perfectly over its width, before material at the centre of the gate proceeded into the die cavity. This can be seen 0.596 second into the shot.

- Taking into account the obstructions in the die cavity, there was a uniform flow of alloy through the die cavity.

- The suspected 'Backflow' phenomenon was not present in the simulation.

The simulation showed that there was a 'peak flow' (but no jet) of molten alloy travelling up the centre of the die during injection and could be seen in the shape of the flow front. This indicated that the inlet gate should, ideally, have been narrower in cross-section, to decrease the the flow up the centre of the die and increase the flow at the sides of the die.

More importantly though, the temperature distribution within the alloy indicated that the alloy passing over the centre ramp features was much hotter (by almost 100^0C) than the alloy passing over the ramp features at the sides of the die cavity. The alloy at the sides of the die was down to 580^0C and was, therefore, travelling much slower due to its decreased fluidity (increased viscosity). This would have an influence on the magnitude of deflection experienced by the laminates at the side of the die-cavity and would explain why the measurements recorded for the laminates in these locations were so low.

The conclusion from this analysis was, therefore, that, in the present set-up, the magnitude of deflection experienced by a laminate protrusion was dependant on its location, in respect to the inlet gate, more than its height.

This deduction was not certain, as the actual flow in the die could not be viewed. It was, however, the only solution to the variabilty in the data which could be drawn based on the hypothesis and had to be remedied if the test-die was going to show the design limits of an un-bonded laminate tool.

To overcome the 'location variable', the experiment had to be modified. This was done by setting all the laminate protrusions, in the test-die, to the same height. This formed the methodology for Experiment Three, discussed in the next chapter.

Chapter 9: Experiment Three: To Establish the Point of Ingress on an Un-bonded Laminate Test-die

9.1 Introduction

For this experiment, it was necessary to modify the laminate test-die to overcome the effect of the variability in the data, based on an up-stand's location within the die cavity. This was done by setting all the laminate protrusions, on all eight-ramp features in the test-die, to the same height for each run. In addition, the analysis of the data was modified, based on the findings from the previous two experiments. This was done by identifying the critical value related to the magnitude of deflection over which ingress and permanent deformation would be certain. This critical value was called the minimum ingress point.

9.2 Objectives

The two objectives for Experiment Three were:

- To conduct a series of runs with the un-bonded laminate test-die to observe at what laminate protrusion height ingress of molten LM24 alloy permanently deforms those laminates.

- To modify the laminate test-die to overcome the effects of the location variable in the laminates identified in the previous two experiments.

9.3 Methodology

Each run consisted of all the laminate protrusions set to the same height above each ramp feature in the die cavity. The first run had all the laminates protruding by 1mm above each ramp feature, the second by 2mm and so on until the sixth run with all the laminates set to 6mm. Any protrusion height, greater than 6mm, was not possible due to the depth restrictions in the cover die.

A total of six runs were completed during which graphs were plotted, after each run, to study the overall effects of deflection. There were no changes in the method by which the castings were produced, sectioned and measured from Experiment Two (Chapter 8). The injection velocity was ramped up, as in the previous two experiments, from the initial injection velocity of 0.8m/s (whilst the die warmed up to its working temperature) up to the working injection velocity of 2m/s, as discussed in Chapter Six.

9.4 Procedure

The results of each run are presented as in Experiment One (Chapter Seven), whereby, the observations from each run are discussed as well as the actual data and plotted graph. A run with the laminates set to 0mm above the ramp feature was not felt necessary, as no ingress had been observed for this height in any of the previous runs.

For each run, a new set of laminate protrusions were inserted into the existing laminate stack behind the ramp features. This was relatively straightforward through the removal of the sliding wedges which clamped the laminates together during casting. Withdrawing the wedges allowed all the laminates to be loosened and also allowed the removal of the two laminates that made up the protrusions behind each ramp feature.

With the new laminate protrusions introduced to the stack, the wedges were re-inserted to clamp the stack together. Clamping the stack to achieve the same compressive load between runs was important. If compression on the laminates should vary, between runs, then this would affect the amount of movement in the laminate stack. This phenomena was discussed in Chapter Six when it was observed that un-bonded laminate stacks can never behave as a solid structure and are more analogous to a compressed spring. If compression varied between runs, then, potentially, so would the way in which the laminates deflected.

Ensuring that the same compressive load was applied after disassembly was done through a torque wrench applied to the five Allen bolts on the sliding wedge at the end of the stack. Once 40Nm (±2Nm) was achieved, then the wedge would have descended far enough between the laminate stack, and the bolster, to be certain of the same compression. This was confirmed, each time, as it was essential to apply the correct amount of compression on the stack so that the holes for the ejector pins aligned with the holes which passed through the bolster to the ejector plate behind.

9.5 The Minimum Ingress Point

No matter where a laminate protrusion was located in the die cavity, it was possible to observe, from the witness marks on the castings, the amount of distance or gap necessary between two laminates before molten alloy would be forced between them to leave a visible witness mark. This point was called the minimum ingress point. Unfortunately, no such increase was observed in the graphs from the first two experiments, due to the overriding influence of the location variable. The castings produced in those runs would, however, show the minimum ingress point, if it existed.

A review of the previous two experiments (runs R_7 and R_8) identified a definite minimum ingress point which was a consistent, and repeatable, measurement found in all the data.

The minimum ingress point can be clearly seen through a review of the witness mark measurements from R_8. From this data a graph was plotted which shows the number of ingress measurements which coincided with each incremental 0.01mm opening between the laminate protrusion and its ramp feature (0.01mm was the smallest measurable unit). This graph is shown in Figure 9.1.

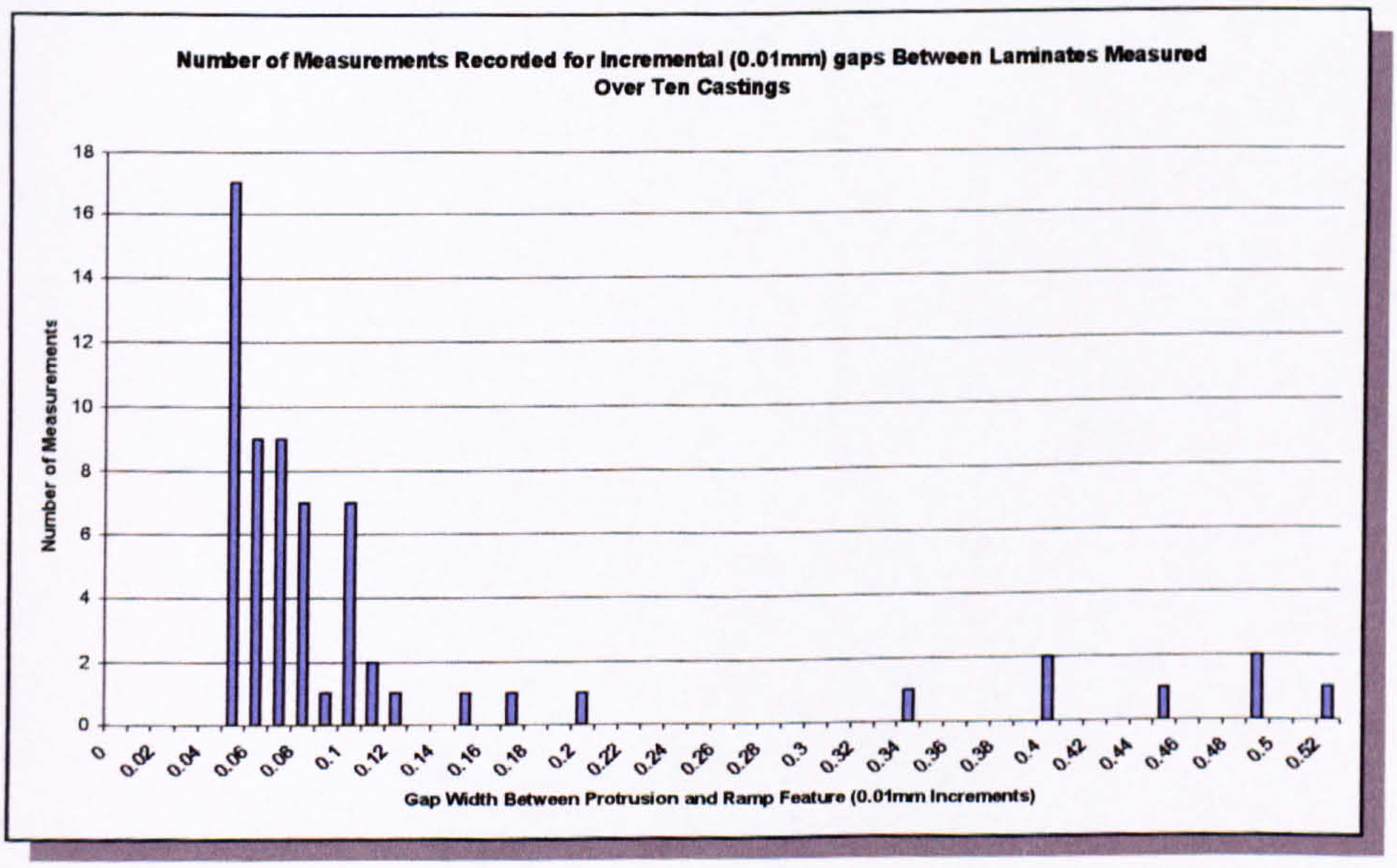


Figure 9.1 Number of measurements for each 0.01mm incremental gap in R_8

The x-axis shows incremental, 0.01mm gap, openings and the y-axis shows the number of measurements taken at each of these increments.

There were no ingress measurements for any gap less than 0.05mm during this run. This graph indicated that, whatever the protrusion height, if any gap opened up between the protrusion and the ramp feature, less than 0.05mm, then the fluidity/wetability of the alloy would be too low to penetrate the gap and leave a witness mark. This finding was born out by the common practice of including very narrow (0.025mm) vents in pressure die-cast dies, discussed in Chapter Five (Section 5.7.2), which allow gasses in the die cavity to escape during the injection phase but are too narrow to allow the passage of pressurised molten alloy to pass.

The run R_7 from Experiment one was also analysed but this run showed a noticeable exception where one of the witness marks measured 0.04mm. To establish why one of the readings should be less than 0.05mm an examination of the witness marks on the castings was performed using scanning electron microscopy (SEM). For the analysis casting R_7C_9 was sectioned and mounted ready for scanning. The complete set of measurements for casting R_7C_9 are shown in Table 9.1.

Up-stand Location	Ingress in mm
A	0
B	0.05
C	0.04
D	0
E	0.07
F	0.11
G	0.06
H	0.06

Table 9.1 Ingress for Casting R_7C_9

The samples prepared from R_7C_9 represented protrusions A, C, B, G, E and F in ingress width order representing witness mark measurements at 0, 0.04, 0.05, 0.06 and 0.11mm. The observations from each up-stand (A through F) are discussed individually in order of width of witness mark. The ingress measurement at up-stand 'F' lies outside the study range but forms a good comparison with the lesser measurements.

9.5.1 Observations for Up-stand 'A'

Up-stand 'A' was measured as having no recordable witness mark. The SEM photograph, in Figure 9.2, clearly shows a smooth rounded edge to the measurement zone (circled in red) where a witness mark would be present if it had occurred.

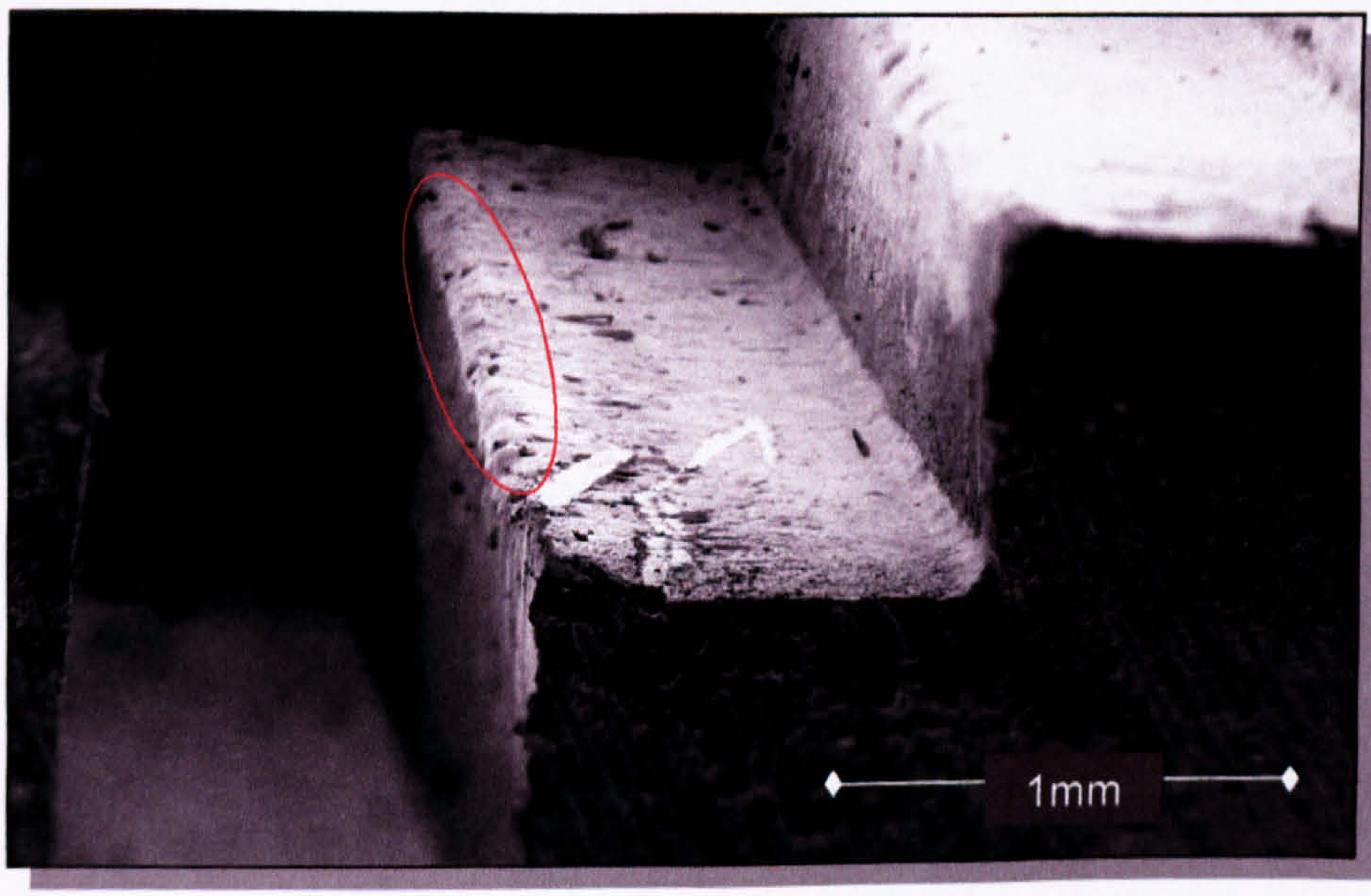


Figure 9.2 SEM photograph showing no recordable ingress

The closest edge of the ingress point in Figure 9.2 shows an upward protrusion. This will be discussed further in the remaining observations. This sample was measured at 0mm ingress as the majority of this sample showed no visible witness mark.

9.5.2 Observations for Up-stand 'C'

Up-stand 'C' was recorded as having a witness mark of 0.04mm and was one of the readings which were considered dubious during measurement under the optical microscope. On the larger ingress measurements (easily resolved by the microscope) ingress appeared as a smooth rounded upward pointing projection in the measurement zone. Though difficult to resolve with an optical microscope, it could be seen that such a rounded feature was not present on the witness mark measured at 0.04mm. This witness mark had a course 'lamella' (i.e. the alloy had been repeatedly folded back on itself) appearance. Figure 9.3 shows the SEM photograph of the 0.04mm witness mark.

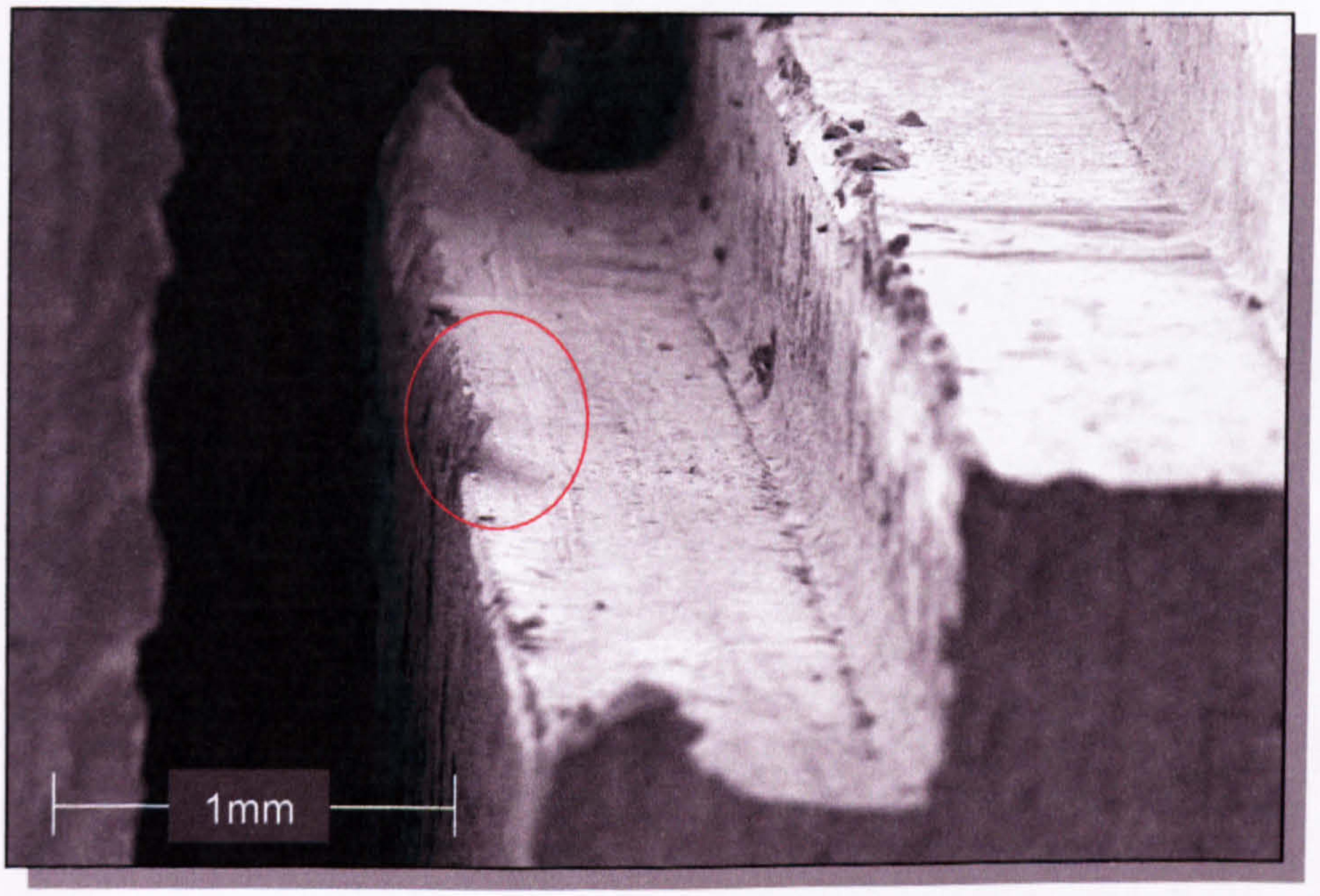


Figure 9.3 SEM photograph showing 0.04mm witness mark

This witness mark did not have the smooth appearance expected for ingress of molten alloy between two laminates. Its identity lies in the circled area in Figure 9.3 in the form of a bulge behind the narrow upward pointing projection of alloy. This was, in fact, a burr caused through the deformation of the casting as it was ejected from the laminate protrusions. This upward movement of the casting, during ejection, created friction between it and the laminate protrusion it had contracted or shrunk onto. This friction was sufficient to deform the casting in the measurement zone creating this distinctive lip and bulge. This can be better seen in an enlargement of this photograph in Figure 9.4.

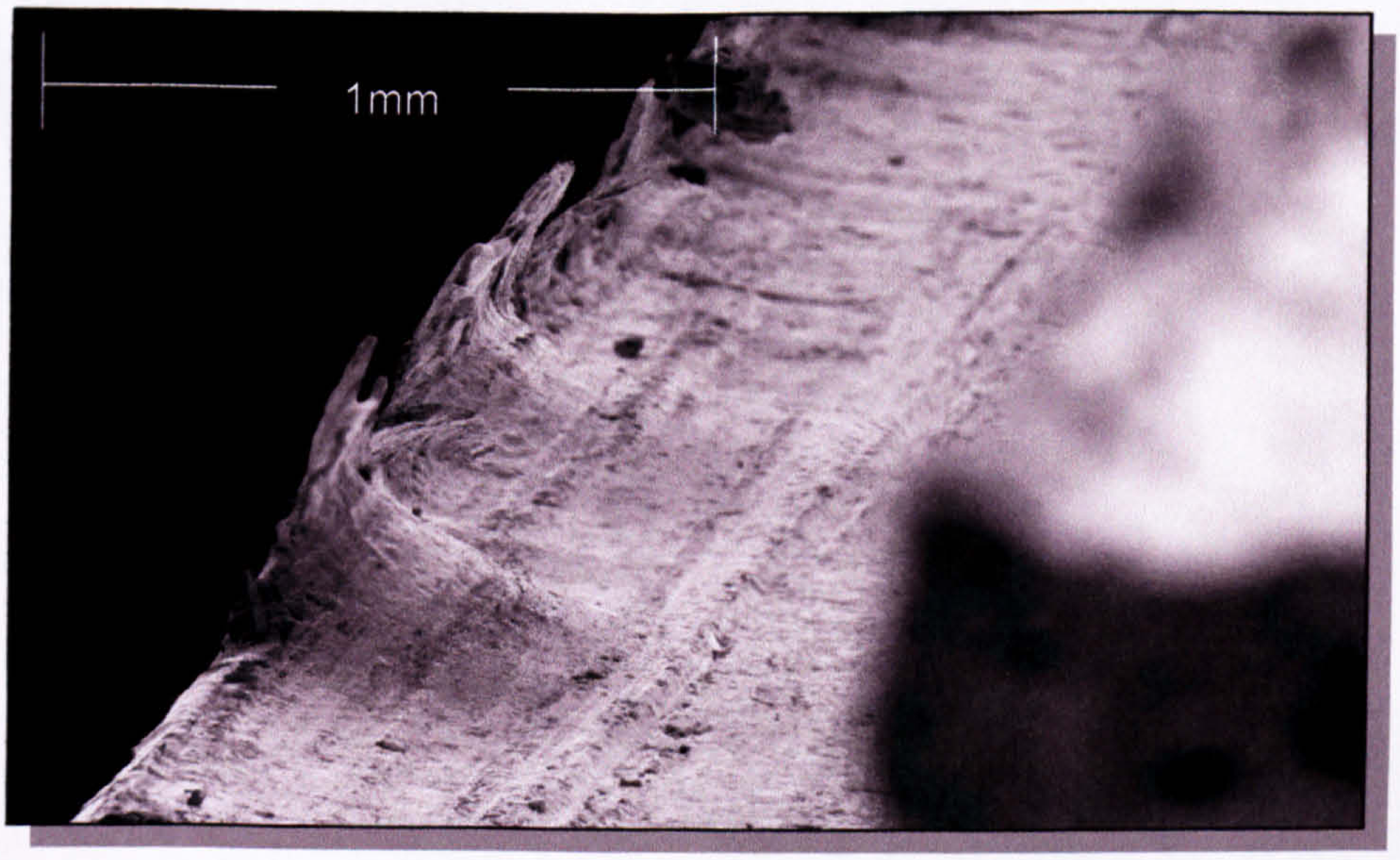


Figure 9.4 Enlargement of Figure 9.3 showing deformation burr

From this photograph it was possible to state, categorically, that this witness mark could not have been caused through ingress and was, therefore, not the minimum ingress point.

9.5.3 Observations for Up-stand 'B'

Up-stand 'B' was recorded as having a witness mark of 0.05mm. Though difficult to resolve under the optical microscope, it was possible to see that this witness mark had a different structure to that of 0.04mm. The witness mark appeared as a shallow ridge of smooth upward projections in the measurement zone and is shown in Figure 4.

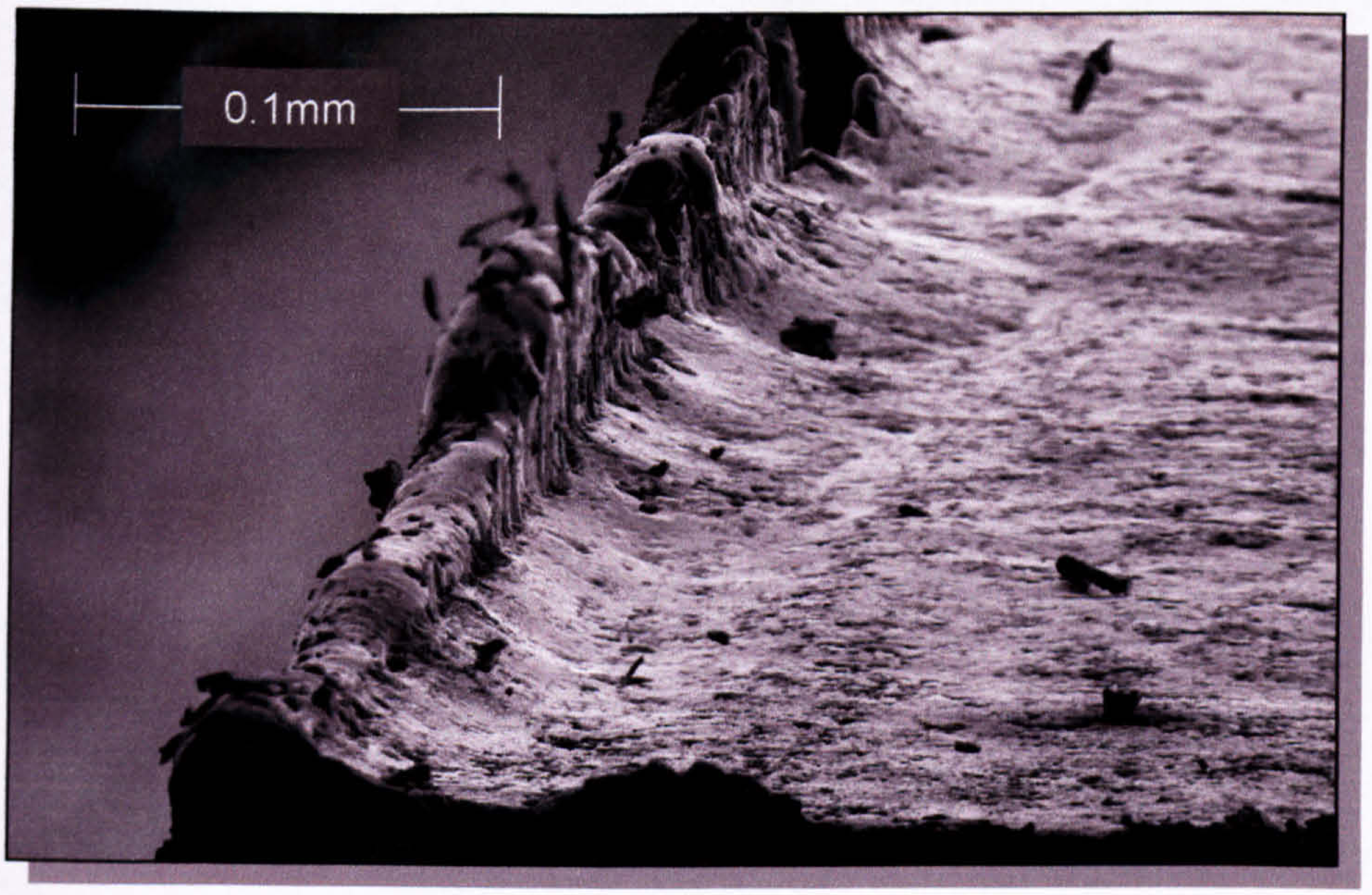


Figure 9.5 SEM photograph of the witness mark at 0.05mm

The photograph shows a witness mark produced through the action of the ingress of molten alloy between the laminate protrusion and its ramp feature. Interestingly, evidence of a deformation burr was not present. The reason why a clear ingress projection should show no sign of deformation during ejection was unclear. But the photograph certainly indicated that 0.05mm may be the minimum point at which ingress occurs in the test-die. This would be confirmed if the witness marks at 0.06mm and 0.07mm showed clear ingress and not a deformation burr.

9.5.4 Observations for Up-stand 'G'

Up-stand 'G' was recorded as having a witness mark 0.06mm wide. Its appearance, under the optical microscope was tall and narrow in profile and the witness mark did not extend across the entire measurement zone. Figure 9.6 shows this witness mark.

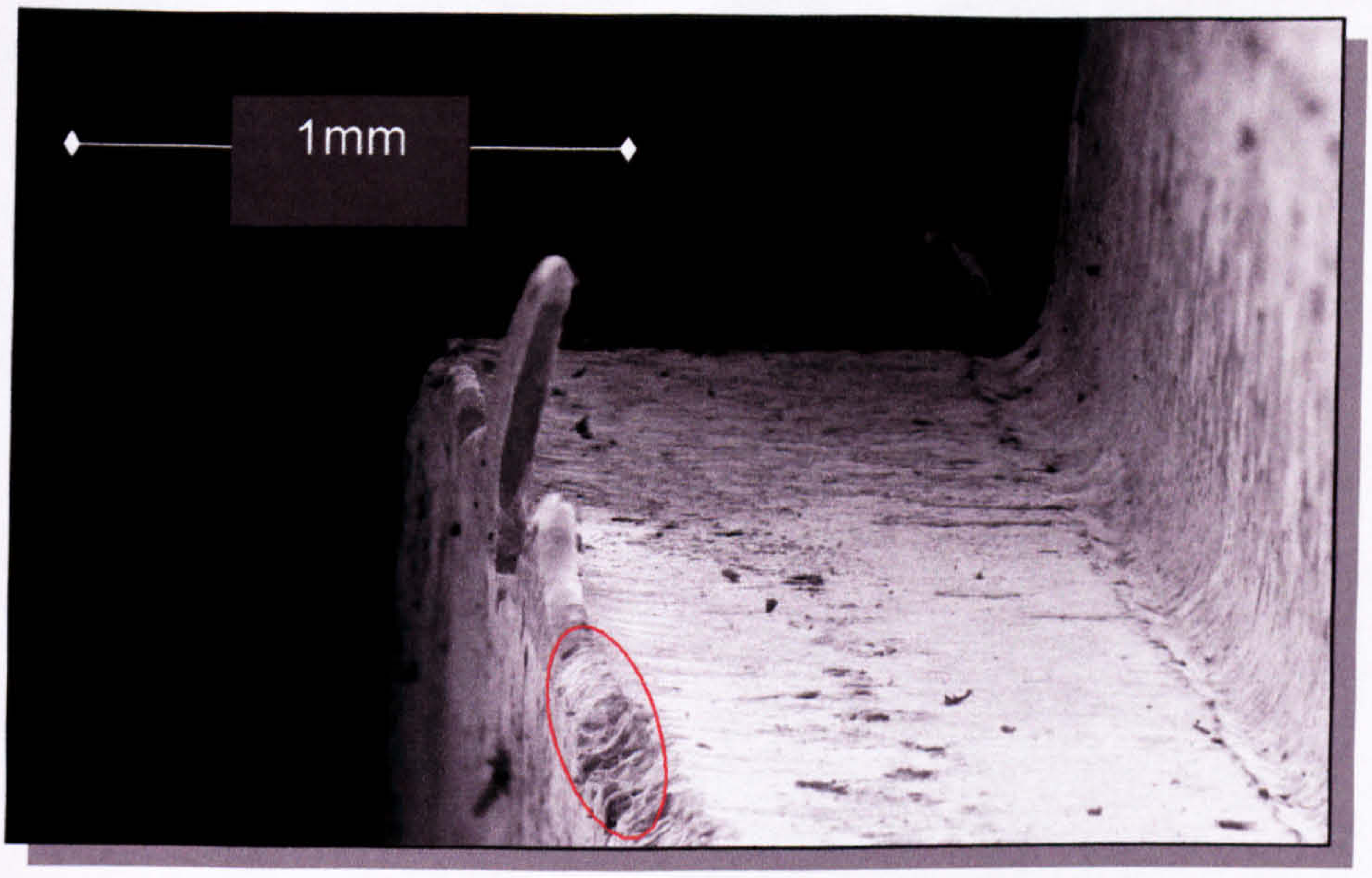


Figure 9.6 SEM photograph of witness mark at 0.06mm

The nearest edge in Figure 9.6 shows where the witness mark discontinued. From the surface of that part of the measurement zone (circled in red) it would appear that the remaining witness mark broke off, in the test-die, during ejection. This was evident by the coarse granular structure at this point. The witness mark which was visible was clearly smooth and rounded in appearance and was exactly what was expected when observing genuine ingress. As with the mark at 0.05mm no deformation burrs were visible but this may have something to do with part of the ingress projection breaking off in the test-die.

9.5.5 Observations for Up-stand 'E'

Up-stand 'E' was recorded as having a witness mark of 0.07mm. This mark was clearly visible under the optical microscope due to its prominence. It formed a complete ridge across the measurement zone and is shown in Figure 9.7.

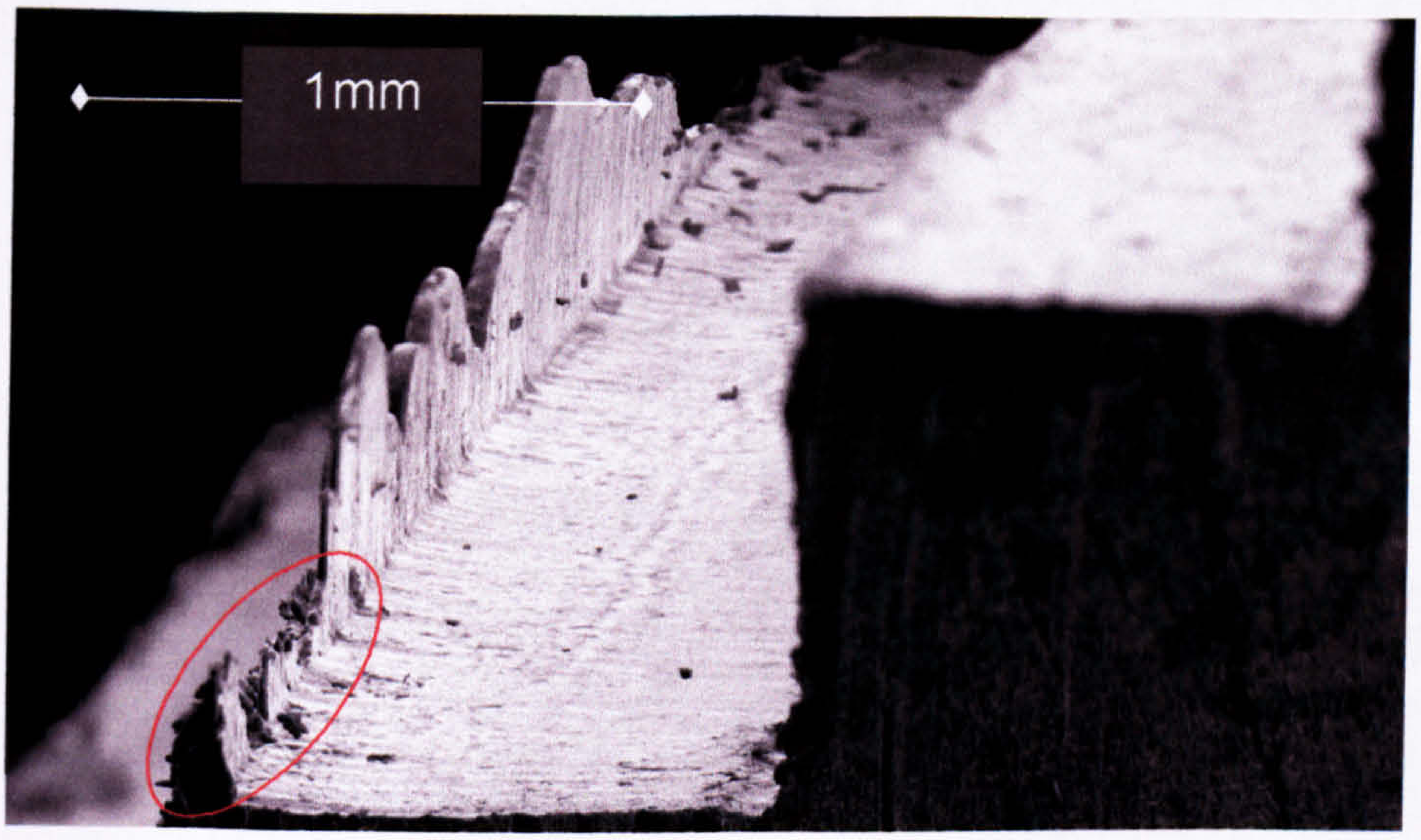


Figure 9.7 SEM photograph of witness mark at 0.07mm

The witness mark for up-stand 'E' shows a ridge of ingress across the entire measurement zone and represented the 'classic' ingress profile which were expected. As in the previous measurement at 0.06mm part of the ingress projection appears to have broken off in the test-die during ejection. Unlike the 0.06mm mark the projection did not break at its base but some way up and is shown circled in red in Figure 9.7.

Again no deformation burrs were evident and this may have been due to the additional support provided to the casting, at this point, by the prominent witness mark.

9.5.6 Observations for Up-stand 'F'

The final observation was up-stand 'F' with a recorded witness mark 0.11mm wide. This mark was included in the study to show the effect of large-scale deflection between a laminate protrusion and its ramp feature and is shown in Figure 9.8.

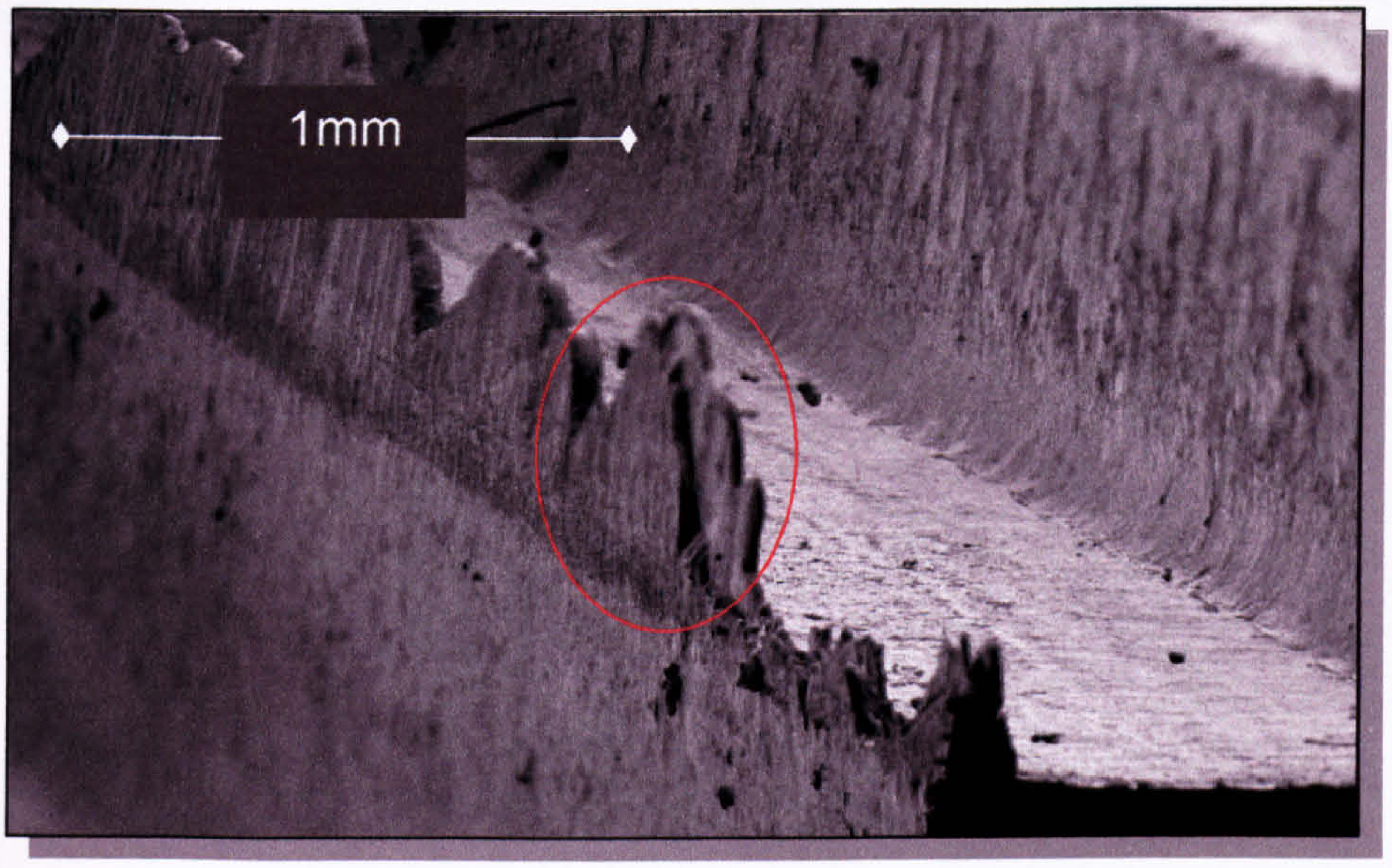


Figure 9.8 SEM photograph of witness mark at 0.11mm

In this example the ingress which occurred was large and indicated that the laminate protrusion had been deflected to such a degree that alloy could fill the gap the opened between them resulting in failure of this particular laminate protrusion. It was interesting to note that ingress possibly occurred twice as indicated by the circled area in Figure 9.8.

The Scanning electron microscope photographs demonstrate that where witness marks appear below 0.05mm they are the result of deformation of the aluminium casting along that plane which is in contact with the laminate up-stand within the test-die during ejection. Therefore, where deflection of an individual laminate is at or greater than 0.05mm then the witness mark will be through the ingress of molten LM24 into the gap it forms. This action leads to the permanent deformation of the feature, as material will commonly break off in the gap formed between the laminates. For consistency, the graphs in this chapter will show any measurements below 0.05mm, for reference only, as they will be deformation burrs as shown in that report and not ingress.

9.6 Results

Up to this point, for each set of ten castings in a run, ingress had been measured for each up-stand location (A through H) within the die cavity. The subsequent graphs for each run were then plotted to show the mean ingress for each up-stand location. The mean ingress for each run was used for the earlier experiments as it was expected that at some protrusion height there would be a noticeable increase from no ingress, to some ingress, occurring.

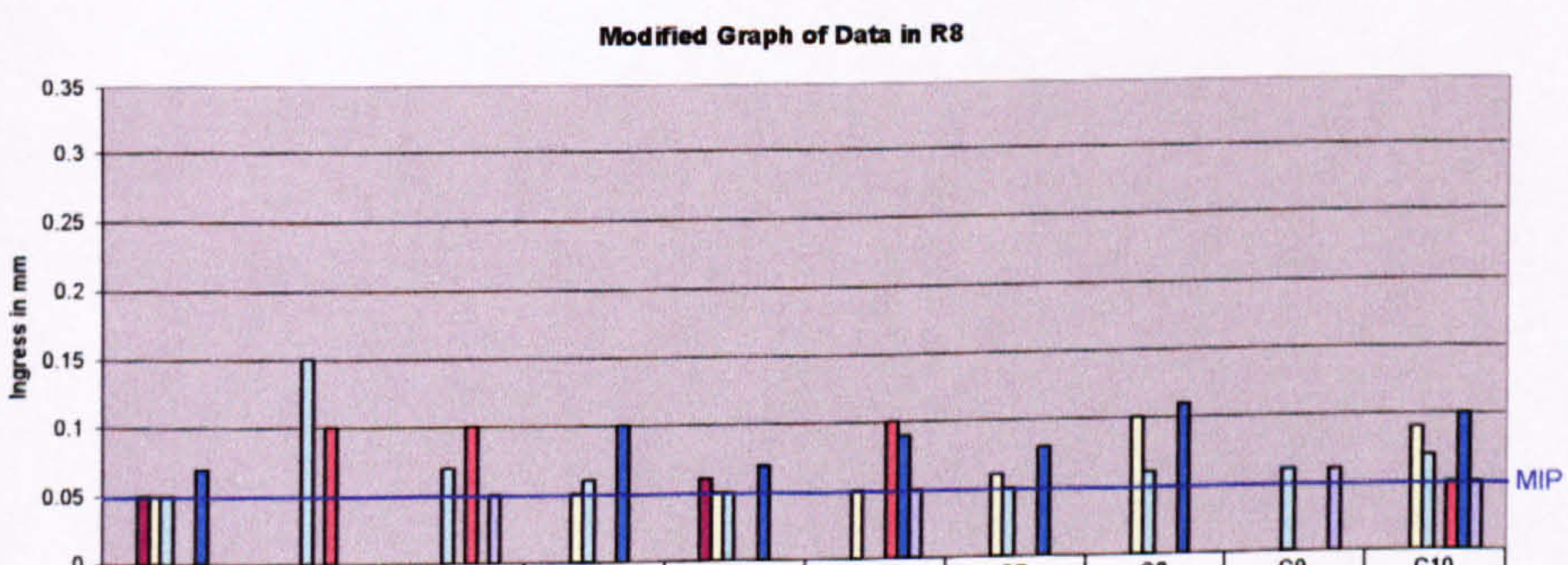
With the minimum ingress point identified, it is necessary to explain how it effected the analysis in Experiment Three. Each run of ten castings, in Experiment Three, generated a total of 80 measurements (8 laminate protrusions by 10 castings). Each measurement indicated either a deformation burr below 0.05mm (the minimum ingress point), no ingress (not shown on the graphs) or, some ingress, if deflection exceeded 0.05mm.

This simplified process meant that each graph, representing a run of ten castings, could be drawn with every ingress measurement shown (instead of the mean, maximum and minimum). Crossing the y-axis at 0.05mm, a horizontal blue line would be used to represent the minimum ingress point. For any run (at 1mm, 2mm, 3mm etc.), if just one of the 80 ingress readings, from the eight ramp features, were greater than this critical value, then for that height ingress and permanent deformation would be an issue and this would define the design limit for an un-bonded laminate die.

Setting the design limits for an un-bonded laminate die, based on the failure of just one laminate at a certain protrusion height, may appear extreme. The fact is, though, that with an un-bonded laminate die in the production or prototyping environment, the die designer must be confident that not one of the laminates will permanently deform during a run no matter where its location in the die is. This could only be done by identifying the first instance that permanent deformation occurred in the laminates in the test-die.

9.6.1 Modification to the Graphical Representation of the Data

In the first two experiments, the data was represented so that the mean deflection could be observed for each up-stand location. For Experiment Three, this would not be necessary, as the location of each up-stand was not relevant to the results and, therefore, the use of the mean ingress figure would not be required, as the implementation of the minimum ingress point meant that it was important to view all the ingress measurements in a run and observe whether any exceeded this critical value. With this in mind, it was felt necessary to change the method by which the data for each run was represented in each graph. Figure 9.9 shows how the data from R_8, in Experiment Two, would appear in this revised format.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0	0	0	0	0	0	0	0	0	0
B	0.05	0	0	0	0.06	0	0	0	0	0
C	0.05	0	0	0.05	0.05	0.05	0.06	0.1	0	0.09
D	0.05	0.15	0.07	0.06	0.05	0	0.05	0.06	0.06	0.07
E	0	0	0	0	0	0	0	0	0	0
F	0	0.1	0.1	0	0	0.1	0	0	0	0.05
G	0.07	0	0	0.1	0.07	0.09	0.08	0.11	0	0.1
H	0	0	0.05	0	0	0.05	0	0	0.06	0.05

Casting Number

Figure 9.9 Revised format showing how data from R_8 would appear

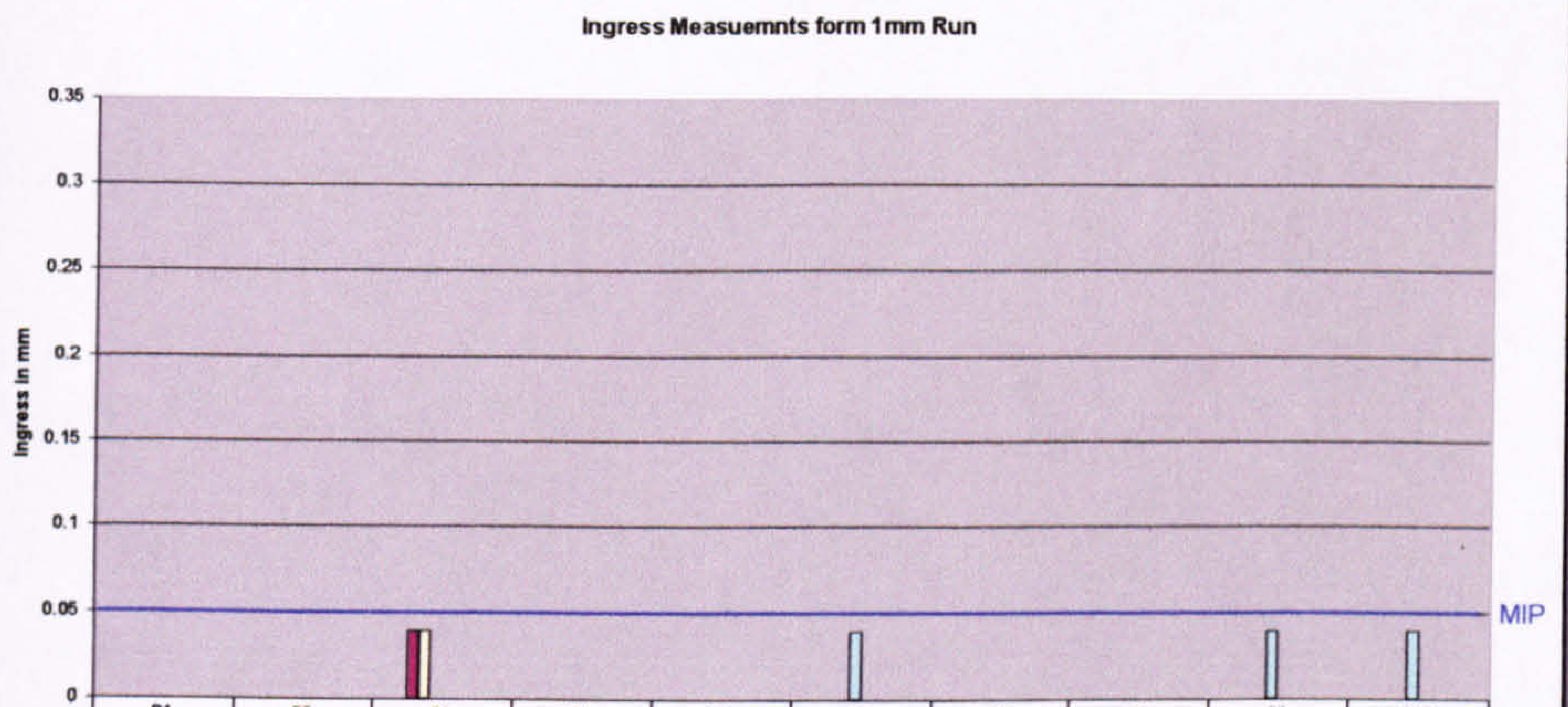
It can be seen that the data has been represented as a bar chart. This allows all the measurements for each casting to be observed against the amount of ingress recorded. The data for each run has been shown, as well as the up-stand location for reference, and, also, the minimum ingress point at 0.05mm (0mm measurements do not register on the graph).

From this graph, an array of different measurements were recorded of which many were over the critical value of 0.05mm.

9.6.2 Observations with Protrusion Height at 1mm

The first run of ten castings, with all the laminates set to 1mm above each ramp feature, was interrupted on three occasions by seizure of the casting in the die. On two occasions, the casting seized in the cover die, and, once, to the ejector side of the test-die. On all three occasions, this meant complete removal of the die block from the machine so that the casting could be salvaged and the run continued.

As to the reasons for the failure, it is unusual for a casting to seize in the cover die as the casting naturally shrinks away from the sides of the die during solidification. In the case of seizure on the ejector die, it appeared that the casting had not had enough time to fully solidify before the automatic ejection cycle was initiated. This conclusion was possible as the ejector pins were forced straight through the casting, without ejecting it off the ramp features. From those ten castings ($C_{1\text{-}10}$), the measurements were taken and the data plotted, as shown in Figure 9.10.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0	0	0	0	0	0	0	0	0	0
B	0	0	0.04	0	0	0	0	0	0	0
C	0	0	0.04	0	0	0	0	0	0	0
D	0	0	0	0	0	0.04	0	0	0.04	0.04
E	0	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0

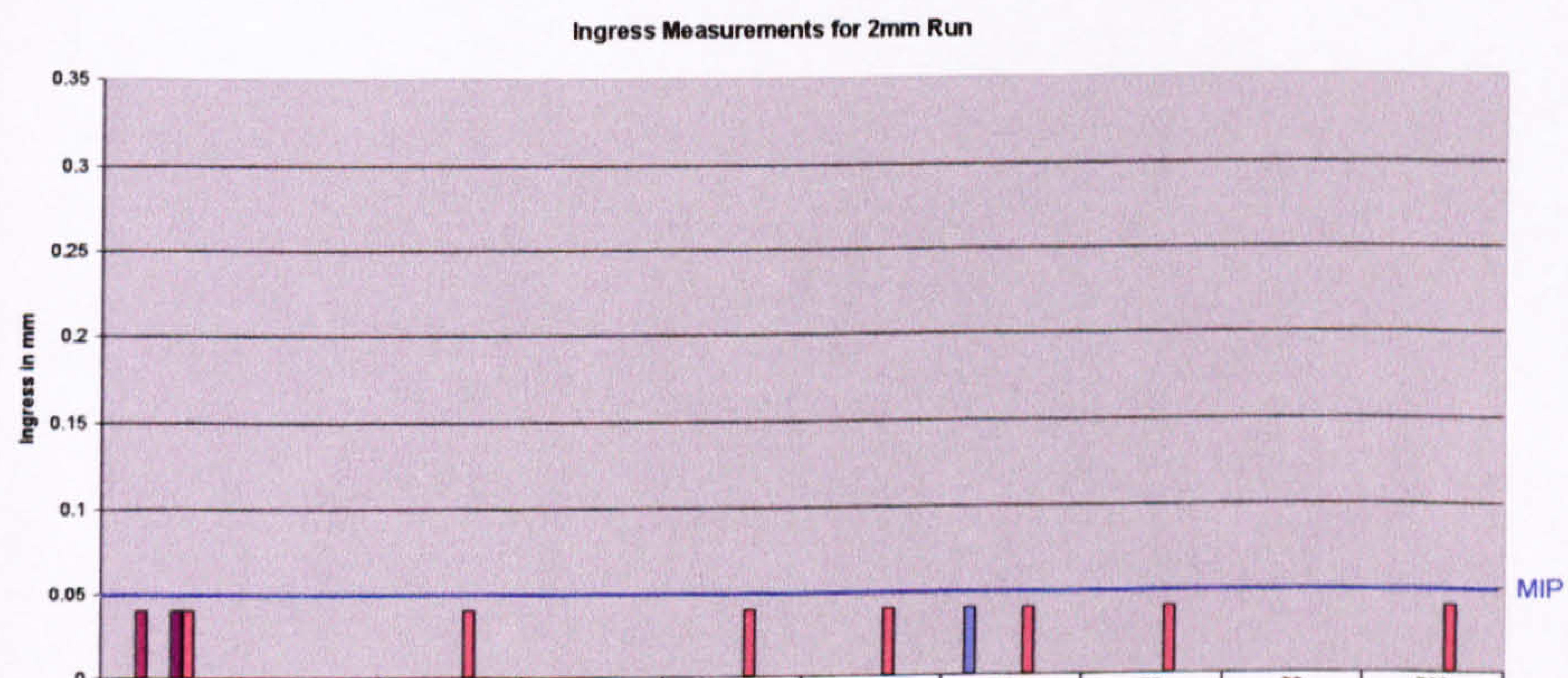
Figure 9.10 Ingress for ten castings from 1mm run

Six measurements register on this graph at 0.04mm. These were confirmed, under the microscope, to be deformation burrs caused through the process of ejection of the casting from the test-die. No measurements register above the minimum ingress point (marked MIP on the graph). The conclusion of this run was that no ingress occurs in an un-bonded laminate structure where a single laminate protrudes by 1mm, no matter where its location in the die cavity.

9.6.3 Observations with Protrusion Height at 2mm

The laminate test-die had a relatively rough surface finish due to the nature of its construction. To overcome the problem of casting seizure on the cover die, the surface of the cover die was hand finished with a grinding tool. The detail on the cover die was not required in the measurement of deflection of the laminate protrusions, as all the detail was on the ejector die. In addition, the release agent on the cover side of the die was changed from the polysiloxane to a more robust Molybdenum paste. Molybdenum paste gives a poor finish to the casting but is an excellent release agent, as it can fill any surface defect preventing seizure on the cover die.

As with the first run, the second run was interrupted by seizure of the casting in either side of the test-die. Seizure in the cover die, therefore, occurred for reasons other than surface finish. Observations were taken during the run to look for a possible reason, with a variety of causes being considered. Ten castings were finally produced, again, culminating with the ejectors punching through the casting which had become seized on the ejector die. From those ten castings ($C_{1\text{-}10}$), the measurements were taken and the data plotted, as shown in Figure 9.11.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0	0	0	0	0	0	0.04	0	0	0
B	0.04	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0
E	0.04	0	0	0	0	0	0	0	0	0
F	0.04	0	0.04	0	0.04	0.04	0.04	0.04	0	0.04
G	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0

Casting Number

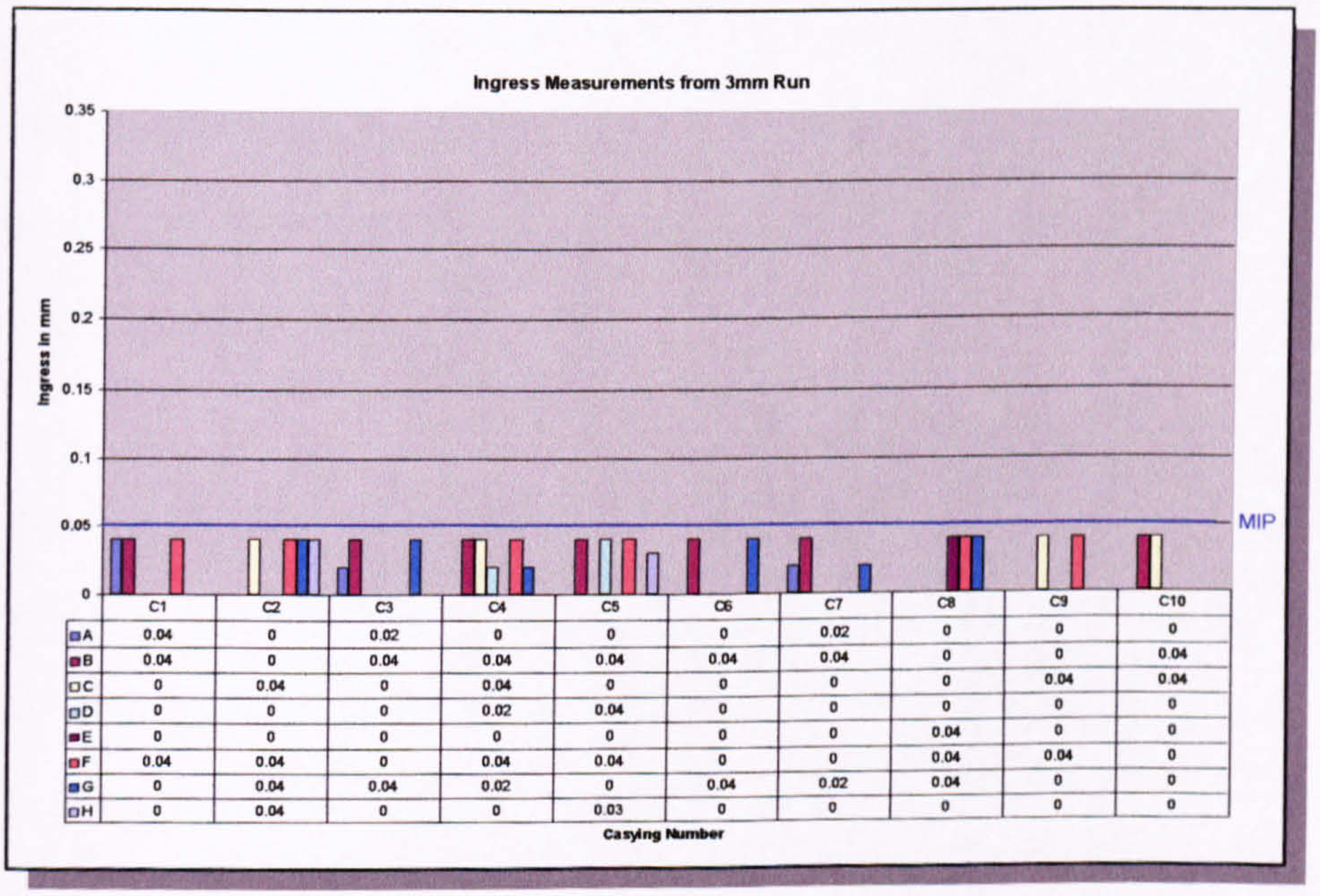
Figure 9.11 Ingress for ten castings from 2mm run

As with the previous run, no ingress occurred between the laminates. Witness marks were measured, caused through deformation during ejection from the ejector die.

9.6.4 Observations with Protrusion Height at 3mm

The die was disassembled and the 3mm laminate protrusions inserted behind the ramp features. Seizure continued to hamper the 3mm run but appeared to be following a pattern with the first and second run. The first few castings would be produced without incidence, then, by the fourth or fifth casting, seizure would result.

A complete run of ten castings were produced. From those ten castings (C_{1-10}), measurements were taken and the data plotted, as shown in Figure 9.12.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0.04	0	0.02	0	0	0	0.02	0	0	0
B	0.04	0	0.04	0.04	0.04	0.04	0.04	0	0	0.04
C	0	0.04	0	0.04	0	0	0	0	0.04	0.04
D	0	0	0	0.02	0.04	0	0	0	0	0
E	0	0	0	0	0	0	0	0.04	0	0
F	0.04	0.04	0	0.04	0.04	0	0	0.04	0.04	0
G	0	0.04	0.04	0.02	0	0.04	0.02	0.04	0	0
H	0	0.04	0	0	0.03	0	0	0	0	0

Figure 9.12 Ingress for ten castings from 3mm run

For this run with 3mm protrusions, there were many values below the minimum ingress point. Numerous readings of 0.04mm and, a few at 0.02mm, appeared. Again, these had to be confirmed as deformation burrs. They were confirmed as burrs and their increased number can be explained by the fact that the casting was ejected from a longer laminate protrusion. This gave a longer distance of ejection to free the casting, leading to increased friction between the laminate protrusion and casting leading to deformation. At 3mm no ingress over the minimum ingress point was observed.

9.6.5 Observations with Protrusion Height at 4mm

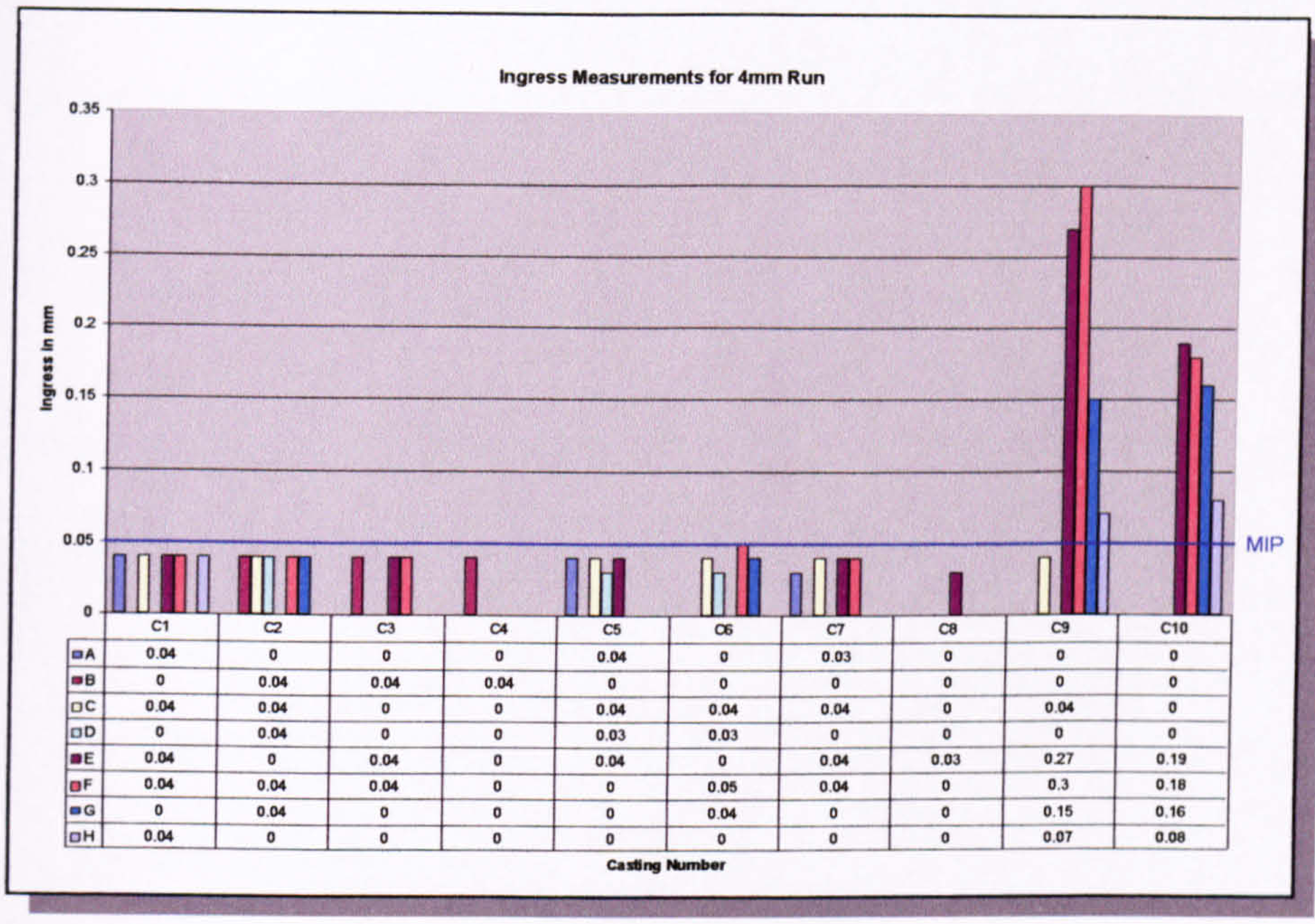
During the previous two runs, the die temperature had come into question. The increased occurrence of seized castings, to both sides of the die, suggested that incomplete solidification of the casting was taking place. This would certainly explain why the ejectors were punching through the casting and would also provide a reasonable explanation for the casting seizing to the cover die. The suspicion as to the cause of seizure to the cover die centred on the fact that if the casting had not completely solidified, before ejection was initiated, then, as the dies opened, the casting would distort. This distortion may have been enough to twist the casting and lock it into the cover die, thus preventing its removal.

As previously stated, it was important to bring the die temperature down to around 175-200^{0}C before each shot was initiated. Touch temperature probes were used on the die surface throughout all the runs, in all three experiments, to check that this temperature was achieved before the next shot was initiated. In addition, cooling was achieved by the liberal application of the water based release agent to the die surface (as no cooling channels existed in the test-die). So how could the die be over-heating if the temperature probes registered the correct casting temperature?

The suspicion was that an error was being made in the assumption that, if the surface probes registered the correct casting temperature, then the rest of the die block was at that temperature. A die block, essentially, is a massive heat reservoir. At the beginning of a run, the entire die block would be at the pre-requisite 175-200^{0}C. As the molten alloy entered the die, its heat would be drawn off and solidification would take place before ejection. Without die cooling, though, each further shot would increase the sub-surface die temperature (shown to be approximately 30^0C per shot in the first experiment) until the molten alloy could no longer solidify in time before ejection took place. The suspected error was that in using surface cooling (via the water in the release agent) only the surface of the die would be at 175-200^0C. When the two halves of the die were closed, the latent heat, still in the mass of the die block, would surge towards the surface taking the die cavity temperature to over 175-200^0C.

If this were the cause of the seized castings then, it could be solved by holding the two halves of the die open longer until the accumulated heat had dissipated out of the die. This approach was felt better than running the die up to seizing temperature, and using the thermocouples to measure a temperature increase before the next shot, as it took so long to remove a seized casting. Up to this point, the entire cycle time was approximately 60 seconds. For this run, the time the dies remained open was increased by an additional 10 seconds per shot to see if seizure could be overcome.

Seizure occurred once, but more importantly, the seizure did not occur until C_8, whereas seizure normally occurred at around C_4 or C_5. The results are shown in Figure 9.13. As with the 3mm run, there was increased incidence of deformation burrs below the minimum ingress point. There were, however, several readings over the critical value of 0.05mm where genuine ingress was measured. These occurred on casting on up-stands E, F, G and H, which are the first laminate protrusions to be struck by the incoming molten LM24 as it enters the die cavity. No ingress occurred in the laminates at the rear of the die cavity. This was to be expected where the location variable has greatest influence on those laminate protrusions closest to the inlet gate.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0.04	0	0	0	0.04	0	0.03	0	0	0
B	0	0.04	0.04	0.04	0	0	0	0	0	0
C	0.04	0.04	0	0	0.04	0.04	0.04	0	0.04	0
D	0	0.04	0	0	0.03	0.03	0	0	0	0
E	0.04	0	0.04	0	0.04	0	0.04	0.03	0.27	0.19
F	0.04	0.04	0.04	0	0	0.05	0.04	0	0.3	0.18
G	0	0.04	0	0	0	0.04	0	0	0.15	0.16
H	0.04	0	0	0	0	0	0	0	0.07	0.08

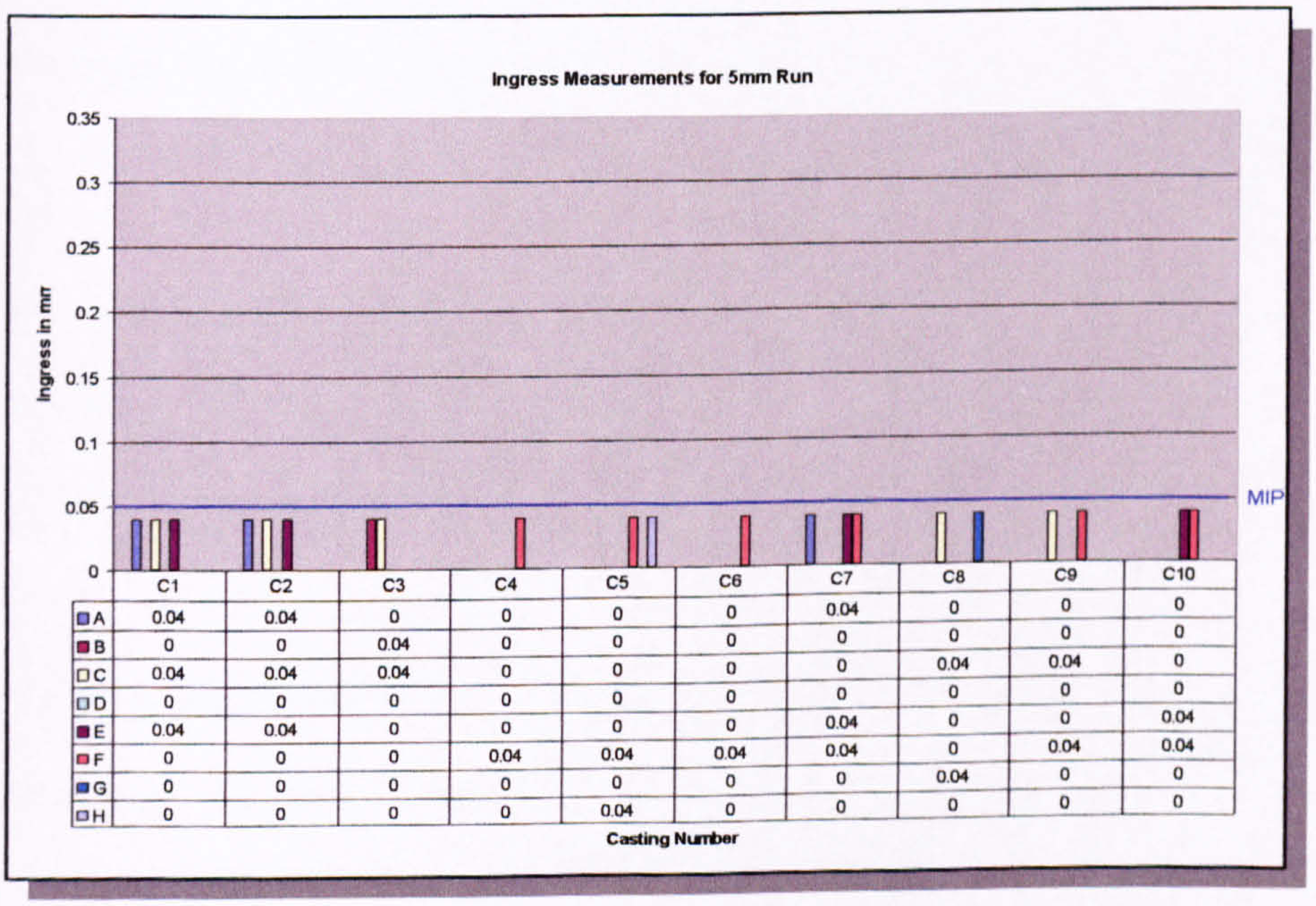
Figure 9.13 Ingress for ten castings from 4mm run

In addition, ingress in laminates E, F, G and H occurred in the last two shots in the run. At this stage, the explanation for this was that either these laminates had been weakened by repeated deflection over the duration of the run, or, that there was some connection between the point at which the casting had seized (i.e. C_8) and the state of the laminate protrusions after C_8 casting had been removed.

Technically, the run was showing permanent deformation within the 4mm laminate protrusions and this would have meant the design limit for an un-bonded laminate die had been reached. There were, however, suspicions in this conclusion, based on the observation that ingress appeared only after the seized casting had been removed from the ejector die. Removing a seized casting requires careful leverage with a range of small wedges which are worked under the casting to prize it up off the ejector die. Great care was taken to ensure that no undue force was applied to the test-die whenever this happened. There was, however, enough doubt in this procedure to require the run at 5mm and 6mm to be performed with the die blocks being held open, between shots, to ensure that the entire block had cooled to 175-200^{0}C, and not just the surface.

9.6.6 Observations with Protrusion Height at 5mm

The 5mm run passed without seizure, due to the close monitoring of the overall die block temperature. Cycle times prior, to this run, were around 60 seconds and this had to be significantly increased with the two halves of the die being held open and the overall die block temperature being monitored until the desired 175-200^{0}C was reached. This resulted in delays as long as five minutes between shots, after the third or fourth continuous casting. The results are shown in Figure 9.14:



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0.04	0.04	0	0	0	0	0.04	0	0	0
B	0	0	0.04	0	0	0	0	0	0	0
C	0.04	0.04	0.04	0	0	0	0	0.04	0.04	0
D	0	0	0	0	0	0	0	0	0	0
E	0.04	0.04	0	0	0	0	0.04	0	0	0.04
F	0	0	0	0.04	0.04	0.04	0.04	0	0.04	0.04
G	0	0	0	0	0	0	0	0.04	0	0
H	0	0	0	0	0.04	0	0	0	0	0

Figure 9.14 Ingress for ten castings from 5mm run

The results of the 5mm run were unexpected. Based on the previous runs, and also on the results in Experiment One and Two, there was expected to have been ingress measurements above the minimum ingress point, where there were actually none. Numerous deformation burrs were observed, as would be expected for laminate protrusions of this length, and these were checked to verify that they were indeed caused through deformation.

As no permanent deformation in any of the laminate protrusions was observed, it was felt a good opportunity to continue the run until ingress occurred. A further ten castings were produced before the alloy in the furnace ran too low and these, too, showed no ingress above the critical value (the data was not plotted here as there is nothing to see except deformation burrs). The outcome for this run presented two possible scenarios:

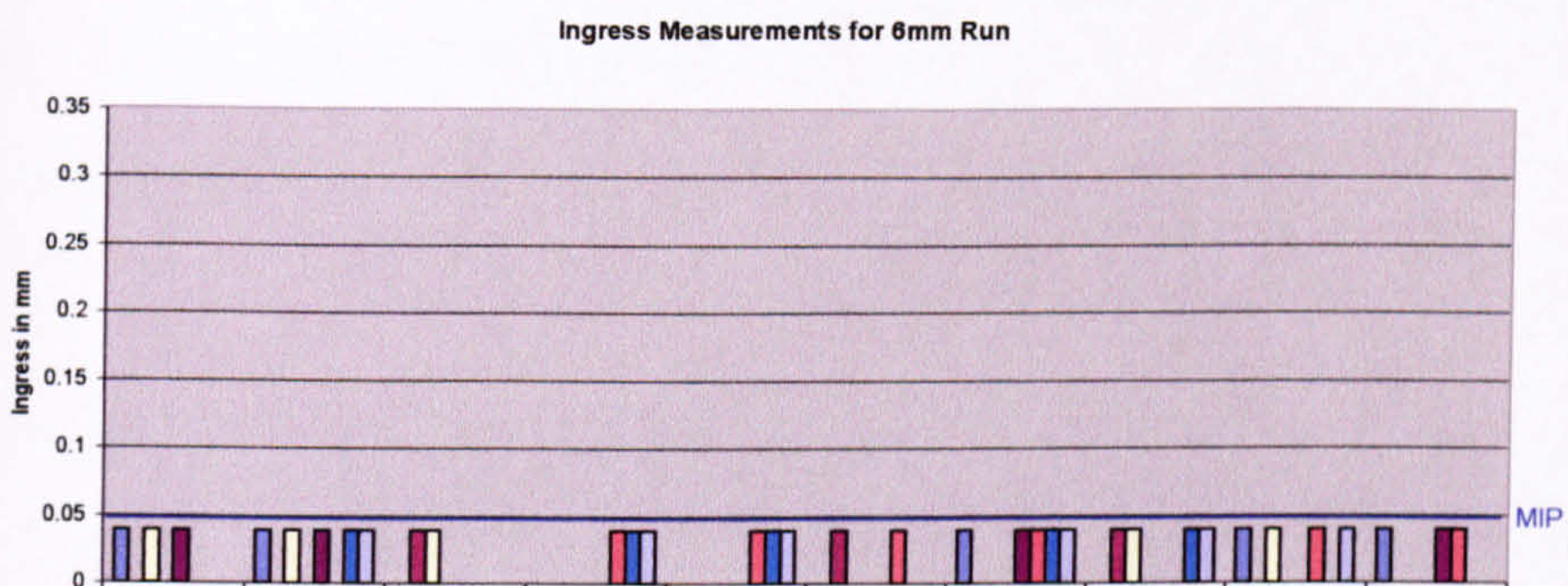
- A phenomenon specific to the 5mm protrusion height was allowing the laminate protrusions to deflect without a gap opening up between the protrusion and the ramp feature.

- The measurements from previous runs with lesser protrusion heights had been corrupted, due to repeated stopping to remove seized castings, and unseen damage was being done to the laminate protrusions.

The simplest way to test these two ideas was to, first, proceed with the run at 6mm and see if ingress occurred. This would strengthen the argument for an unaccounted phenomenon at 5mm. If no ingress occurred at these greater heights (a 6mm free moving protrusion height is going to receive a large amount of deflection where injection forces are 2m/s) then the second hypothesis would be applicable.

9.6.7 Observations with Protrusion Height at 6mm

The die was, again, run using the extended dwell times between shots and, again, no seizures occurred, resulting in very high quality castings throughout the run. The following measurements were taken and plotted in Figure 9.15.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A	0.04	0.04	0	0	0	0	0.04	0	0.04	0.04
B	0	0	0.04	0	0	0.04	0	0.04	0	0
C	0.04	0.04	0.04	0	0	0	0	0.04	0.04	0
D	0	0	0	0	0	0	0	0	0	0
E	0.04	0.04	0	0	0	0	0.04	0	0	0.04
F	0	0	0	0.04	0.04	0.04	0.04	0	0.04	0.04
G	0	0.04	0	0.04	0.04	0	0.04	0.04	0	0
H	0	0.04	0	0.04	0.04	0	0.04	0.04	0.04	0

Figure 9.15 Ingress for ten castings from 6mm run

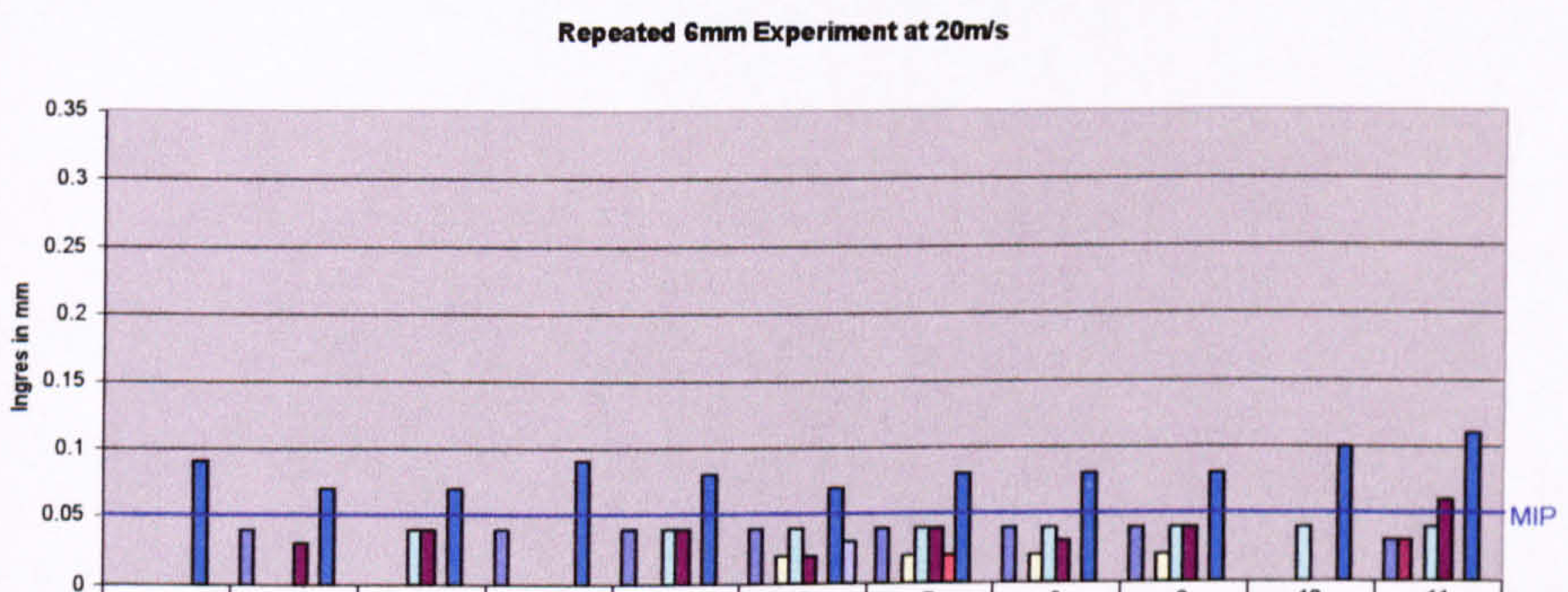
With a 6mm laminate protrusion height, no ingress was recorded for the entire run of ten castings. As predicted earlier, there was an increased occurrence of deformation burrs at the 0.04mm mark. This was to be expected in the taller 6mm protrusions. The deformation burrs required careful study (a course lamella structure is seen under the microscope and not the smooth finish where ingress occurs), as the extra distance the casting moved before it fell clear of the laminate protrusions meant that some of the burrs were reading closer to 0.045mm than 0.04mm (this was very close to the minimum ingress point at 0.05mm). For the sake of clarity, these wider deformation burrs were recorded at 0.04mm to distinguish them from any genuine 0.05mm ingress readings.

The conclusion of this run was that the hypothesis relating to a specific phenomenon at 5mm could be discounted, and, that the reason for ingress in the 4mm run (and to some degree the first two experiments) was caused through the repeated stopping of the run to physically remove entrapped castings. Though done with great care, the act of forcing off the casting from the die must have damaged the laminate protrusions in some way (no sign of damage was ever observed) leading to a false ingress measurement. Removal of a seized casting in a production die requires great skill.

To verify that the integrity of the test-die was being corrupted, through the process of removal of a seized casting, the test-die was set up once more to repeat the 4mm run. During this run, the total die block temperature was monitored before each shot was initiated. No castings seized, during the ten castings which were taken. The castings were sectioned and no ingress was present on any of the castings. The actual measurements, or a plotted graph, are not shown as no ingress occurred during this run.

Though outside the scope of this experiment, as the injection velocity had to remain constant over all the runs (this was one of the fixed variables), a final run was conducted with the laminates set at the maximum protrusion height of 6mm. During this run the injection velocity was ramped from 2m/s up to 20m/s. This was ten times faster than the test velocity and is used in high production environments. The results from this run are shown in Figure 9.16.

This final run does verify that no ingress occurred throughout the entire run. However, the graph is misleading as there is clearly a 'spike' representing ingress greater than 0.05mm on each casting at ramp 'D' (shown as the dark blue column). This spike can be discounted as a viable affect of ingress as it was present from the outset of the run (C_1) and is an indication of a problem with that particular laminate. If ingress had been measured, at ramp 'D', beginning midway through the run then this would have been a clear indication of ingress being caused, directly, through this laminate deflecting during the casting cycle. This did not occur and, therefore, this run supports the finding that, even at elevated injection pressures, ingress does not occur with the laminates protruding above each ramp feature by 6mm.



	1	2	3	4	5	6	7	8	9	10	11
A	0	0.04	0	0.04	0.04	0.04	0.04	0.04	0.04	0	0.03
E	0	0	0	0	0	0	0	0	0	0	0.03
B	0	0	0	0	0	0.02	0.02	0.02	0.02	0	0
F	0	0	0.04	0	0.04	0.04	0.04	0.04	0.04	0.04	0.04
C	0	0.03	0.04	0	0.04	0.02	0.04	0.03	0.04	0	0.06
G	0	0	0	0	0	0	0.02	0	0	0	0
D	0.09	0.07	0.07	0.09	0.08	0.07	0.08	0.08	0.08	0.1	0.11
H	0	0	0	0	0	0.03	0	0	0	0	0

Casting Number

Figure 9.16 Repeated 6mm run with injection velocity increased to 20m/s

9.7 Conclusions

The immediate conclusions which were drawn from Experiment Three were:

- Assuming deflection occurs on an individual laminate protrusion (as it can't be observed directly), through the action and flow of molten alloy, no ingress results even on laminate protrusions standing 6mm above their neighbouring laminates.

- For ingress to occur between two laminates, irrespective of the laminate's protrusion above its neighbours, the laminate must be forced far enough back for a gap of at least 0.05mm to open up to allow the free flow of molten alloy down that gap.

- The act of removing a seized casting can damage the effectiveness of the laminates in a laminate die to resist deflection and subsequent ingress.

- The measurements for ingress in previous runs would appear to be erroneous, caused through repeated seizure of the casting and the overheating of the die blocks during a run.

- Even with the location variable complicating the magnitude of deflection of an individual laminate, it had no influence on laminate protrusions at or less than 6mm above its neighbours.

These findings far exceeded the expectations for the concept an of un-bonded laminate tool for High Pressure Die-casting applications. It was unfortunate that when the test-die was designed, the 6mm limit was identified as far greater than the height at which ingress would occur.

Chapter 10: Discussion

10.1 Appraisal of the Experimental Results

The intention of Experiment One was to ascertain the feasibility of the laminate test-die under high-pressure die-casting conditions. An un-bonded laminate test die was designed and constructed to run on a production High Pressure Die-casting machine. A total of seven runs of ten castings in each run was performed (over 70 shots including those that were incomplete). The experiment was terminated, prematurely, through failure of both the die-casting machine and the furnace used to melt the LM24 alloy but it did show that the first objective for this study could be met.

During each of the seven runs, observations were made as to the condition of the test-die, and, on certain occasions, the laminate protrusions were exchanged on the eight ramp features within the die cavity as they were showing signs of deflection and ingress. Though the die performed well it was impossible to ascertain exactly at what protrusion height ingress was occurring, as many of the castings were incomplete. This was mainly down to the fact that the process was difficult to control.

The conclusions, from Experiment One (Chapter Seven), were that an un-bonded Laminate Tool could withstand High-Pressure Die-casting. Deformation was observed in some of the laminate protrusions but in the remainder of the laminates, which made up the die (in particular those laminates that made up the ramp features), no permanent deformation or ingress was observed. What could not be established, at this stage, was the laminate protrusion height at which ingress began to affect the performance of the tool.

From the measurements plotted from the first set of ten complete castings, ingress was expected to become apparent at some 'minimum ingress point', any deflection in the laminates below this distance would result in no measurable witness mark on the casting. If deflection were above this point, then ingress would be measurable on the casting. There should have been no ingress measurements for the lowest laminate protrusions and ingress on the tallest protrusions. Between these two extremes, there should have been some noticeable increase from no ingress to some ingress. The analysis of this run showed no correlation between the protrusion height and the size of witness mark recorded in the casting.

The evidence pointed to problems with the die-casting machine used, which had, failed. The performance of the machine was analysed from the data gathered from the load cells in the test-die, which confirmed that the overriding variable was the EMB machine itself (it was twenty years old). For this reason, the objective of Experiment Two was to run the test-die, in the same set-up, on a more consistent high-pressure die-casting machine.

For Experiment Two, experiments were undertaken on a Frech 125 DAK hydraulic high-pressure die-casting machine. From the initial runs, it was clear that this machine performed consistently, as would be expected in a modern die-casting machine.

However, as with Experiment One, there was no correlation between a laminate protrusion's height and the amount of deflection experienced by it. This led to the conclusion that a further variable was influencing the outcomes of the experiment. Bearing in mind that it was impossible to see the flow of molten alloy around the die during each shot, an extensive analysis was conducted to identify the additional variable by physical measurement of the die and by computational fluid dynamics analysis.

This analysis identified that the deflection experienced by an individual laminate was more dependent on the laminate's location in the die cavity in respect to its proximity to the inlet gate.

Based on the conclusions from Experiment Two, a third experiment was conceived. To overcome the location variable, all the laminate protrusions were set to the same height for each run.

The analysis indicated that, whatever the protrusion height, if any gap opened up between a laminate protrusion and its ramp feature less than 0.05mm, then the fluidity of the alloy would be too low to penetrate the gap and leave a witness mark on the casting. Therefore, 0.05mm was deemed the minimum ingress point. This meant that instead of trying to observe an increase in the mean measurements, for each up-stand location in the plotted graphs (as had been done for the previous experiments), all the measurements from a run could be represented graphically and compared to a horizontal line crossing the y-axis at 0.05mm.

With an up-stand of 1mm, 2mm or 3mm no witness marks (indicating ingress) were present on any of the castings. The first three runs were interrupted, however, through the casting seizing to either the cover or ejector die, on more than one occasion.

On the 4mm run, the dwell times (time the dies remain open between shots) were extended to observe the effect of dissipating this build up of heat from deep within the die. During this run, only one casting seized.

In castings from the 4mm run, castings C_9 and C_{10}, showed clear and measurable witness marks caused through ingress. This would suggest that, at 4mm, the laminate protrusions failed to stand up to the casting process. However, there were suspicions that these witness marks appeared directly after casting C_8 seized and had to be removed which possibly indicated that some of the laminates had been damaged slightly during the removal of casting C_8. For this reason, the experiment was continued and the runs at 5mm and 6mm were performed.

For the 5mm and 6mm runs, the dwell times were extended to ensure that all latent heat in the die was dissipated between shots. This meant delaying each shot, by as much as five minutes, before the entire die block had cooled to 175-200^{0}C and not just the surface. Both runs went uninterrupted, producing a set of ten high quality castings. These were sectioned and measured with no ingress being recorded. To verify that the laminates in the test-die had been damaged during removal of the seized casting during the 4mm run, the 4mm experiment was repeated, using the extended dwell time. No ingress occurred in any of the castings on this repeated run.

As the protrusion heights could not be increased above 6mm, a further set of castings with the 6mm protrusions was conducted but with the injection velocity being increased from 2m/s (this was a variable that had to be fixed) to 20m/s. This velocity is used in high production environments and, again, no ingress was recorded.

10.2 The Key Findings

This research has shown that the concept of Laminate Tooling could be applied to pressure die-casting as a design verification tool. In particular, the tool was un-bonded so that the flexibility benefits of exchangeable laminates and features could be assessed. Through all the runs, the tool showed that the laminates could be readily loosened and new laminates inserted. The test-die produced over ninety castings and, therefore, met the primary objective laid down in Chapter Six.

Experiments Two, and Three, attempted to address the design limitations of an un-bonded laminate tool through the analysis of the laminate test-die, under 'worst-case' scenario conditions. This involved the examination of a series of laminate protrusions, set at incremental heights above a laminate ramp feature, built into the test-die. The secondary objective was to observe at what protrusion height an isolated laminate would deflect to the point that ingress of molten alloy and permanent deformation would render the tool unusable in die-casting condition.

No ingress and permanent deformation was observed in any of the laminate protrusions up to 6mm above each ramp feature. Allowing the tool to cool properly is important to avoid damage to laminates during the removal of castings that may seize to either the cover or ejector die.

Chapter 11: Conclusions

The conclusions from this research were:

1. An un-bonded laminate tool can withstand the conditions found in High Pressure Die-casting and be used for short runs for design verification.

2. Isolated individual laminates of 1mm thick H13 may be susceptible to ingress of molten alloy should they stand 6mm or greater above their neighbour, though special consideration must be given to the stiffening of laminates as their thickness increases or decreases.

3. For ingress to occur between two laminates, irrespective of the laminate's protrusion above its neighbours, the laminate must be deflected for a gap of at least 0.05mm to open up to allow the LM24 aluminium alloy to enter that gap.

4. Within any given die design deflection of the laminates that make up the die will be more influenced by the laminate's proximity to the inlet gate than the laminates protrusion height above the laminate it abuts.

5. The act of removing a seized casting can damage the effectiveness of the laminates in a laminate die, to resist deflection and subsequent ingress.

For prototype tooling and tooling for short production runs, where features do not protrude greater than 6mm, then this research has shown that an un-bonded laminate structure will withstand high pressure die-casting where 1mm thick H13 tool steel sheet is employed. The protrusion height of any laminate in an un-bonded laminate tool will increase as the thickness of the laminates are increased and naturally decrease if thinner sheet material is used than 1mm H13. However, part of this project concluded that where strength and detail (reduced stepping) are required in a prototype tool (and no finishing) then only H13 grades at or thicker than 1mm are available.

This fits in with the prototyping concept in that the construction time should be fast, low cost, with minimum finishing and include the ability to change individual or groups of laminates to alter the flow, profile or geometry of the tool under examination.

The investigation into un-bonded laminate tooling for high pressure die-casting was undertaken as the fundamental research behind the issue of bonding laminate tools to withstand extended use in the pressure die-casting environment. In addition, during the formative stages of this research, it was felt that laminate tooling could offer added advantages over conventional tooling (such as conformal cooling channels) but would need bonding to prevent the laminates from deforming during any secondary machining operation required to produce castings with a good finish. This work has shown that where design appraisal tooling is required them leaving the tool un-bonded is possible within the parameters established by this work (i.e. 6mm protrusions with 1mm H13 sheet). Where a design requires isolated laminates protruding greater than 6mm (though rare) then the design would need some modification, if a prototype laminate tool is required. This, therefore, implies that if the design could not be modified to reduce the protrusion height to 6mm then bonding of the laminates would be necessary. If this were the case then it is likely that features within the tool could not be replaced to assess different designs before the long run tooling is made.

In line with the objectives an un-bonded tool was designed and constructed with an array of features that represented the worst case scenario that a laminate die may experience in the pressure die-casting process. A total of 90 castings were produced from the test-die with over 120 castings, to date.

The latter part of the study showed that even though lower injection speeds (2m/s) were used for the experiments, this speed could be increased to high production speeds of 20m/s, again, with no adverse affect on the laminates in the die. In addition, the un-bonded laminate die was run on a horizontal 'cold-chamber' high pressure die-casting machine using LM24 casting alloy. This alloy is the most difficult die-casting alloy to use due to its high melting point, high injection pressures and corrosiveness to steel dies. Equally, the Laminate Tooling concept can also be applied to all the pressure die-casting processes currently used as all use either zinc or magnesium alloys at lower injection pressures or lower melting points than LM24 aluminium alloy (even though there are differences in the fluidity of these alloys compared to LM24).

The possibility of an un-bonded laminate tool for die design verification or even 'short run tooling' has been shown. Not only does this concept allow multiple iterations of a die design to be appraised but it also allows for the production of prototype castings with exactly the same physical and mechanical properties as fully die-cast parts. This ability has not been previously possible through the traditional use of sand and investment casting and plaster moulding to replicate die-cast parts which has hindered accurate 'fit, form and function' analysis.

The study also identified the use of a sliding wedge arrangement to constrain the laminates within a solid bolster. This is a new and novel technique that has not been applied to Laminate Tooling before. The process enables accurate and repeatable clamping of the laminates that make up the tool as well as a rapid method to exchange the laminates that make up a feature, inlet gate, runners or even the orientation of a feature to the inlet gate within the tool.

Finally, the laminate test-die took two weeks to design and construct. Much of this time was taken in constructing the bolster assembly in which the laminates were constrained. Further iterations, through the exchange of laminates within the tool, would only require new laminate profiles to be cut with the same bolster being used repeatedly. In addition the cost of the laminate test-die was £4,500 and again much of this cost was absorbed in the initial construction of the bolster. Further iterations on a die design would cost significantly less to implement. These figures would certainly allow the possibility to consider multiple iterations for a die design to ensure that by the time the production tooling was running its longevity would be assured.

Chapter 12: Recommendations for Further Work

In recommending areas of future research the first step would be to expand on the second objective of this study which was to identify the design limits for an un-bonded laminate tool.

Further research areas include:

1. The effects that different geometric features and aspect ratios will have on the performance of an un-bonded laminate tool.

2. The performance of un-bonded Laminate Tooling under extended use in pressure die-casting applications.

3. Exploiting the resilience in un-bonded Laminate Tooling for pressure die-casting applications by resisting crack propagation.

4. Inter-laminar bonding techniques of Laminate Tooling for pressure die-casting applications.

5. The use and development of solid and exchangeable die inserts in a laminate tool.

6. The consequences of laminate orientation in a tool for pressure die-casting.

7. Material selection for Laminate Tooling in pressure die-casting applications.

8. The inclusion and optimum layout of conformal cooling channels in Laminate Tooling for pressure die-casting applications.

9. Secondary finishing of Laminate Tooling.

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Appendix I: Internal Report for the USCAR Consortium - Bonding of sheet steel using fused silicates

1. Abstract

Work was carried out to assess the possibility of bonding stacks of H13 laminate steel sheet using sodium silicate and silica/enamel preparations for use in the pressure die-casting of aluminium.

2. Introduction

An assessment was made as to the suitability of using fused sodium silicates to bond individual laminates which make up a tool. The objective was to ascertain whether the laminates which make up a die-cast die could be bonded so that they behave as a solid block. Suitable bonding media for steel sheet can be divided into three categories:

- Adhesive Bonding,
- Brazing and Soldering,
- Solid Phase Welding.

This report covers the first category, the second two categories are covered in parallel papers which can be found in the author's papers reproduced at the end of this thesis. Average temperatures within the operation of pressure die-casting vary depending on the type of machine, the degree of cooling used within the die, the speed of operation and the material used. For the USCAR project, the consortium were specifically looking at the use of LM24 aluminium alloy. LM24 has a melting point of 690^{0}C and even though a shot may be initiated with a die temperature of 175-200^{0}C, the consortium specified an average die temperature of 300-350^{0}C. At these temperatures very few adhesives exist that can operate above 250^{0}C.

3. Background to this Study

Interviews were conducted with one of the industry leaders-The Ferro Corporation, IPEC Laboratories, van Helmontstraat 20 3029 AB, Rotterdam, Netherlands.

Ten years ago they developed laminate armatures for underwater motors and worked for English Electric to bond stacks of silicon steel. However, these applications were operating at or near room temperature. They electro-statically coated the laminates with enamel powder and then heated the stack to its transition point for about 2-3 minutes.

Most enamels work comfortably up to 550^{0}C after which softening occurs. This does not mean that the bond is affected but it does degrade rapidly at 800^{0}C. The problem is that they work well in compression but very poorly in tension. On enamel coated steel utensils, a mismatch in thermal expansion is used so that heat is absorbed into the enamel layer before the steel substrate, thus placing the enamel under a compressive load. The trick with bonding steel sheet with enamels would be to keep the enamel layer as thin as possible to reduce the thermal mismatch.

Work has also been done to bond laminates by applying 50-70 microns of sodium silicate based enamel to the surface of the sheet steel and then heating them, individually, to get a good bond onto the steel. The laminates were then stacked and bolted to retain their shape and heated to the transition point so that a good bond was achieved throughout. Limitations of the process were the cleanliness of the steel - there can be no grease or rust as it can affect the oxidation of the glass on cooling. Also, the amount of carbon in the steel must be below 0.08%, with no chromium present. Nickel and Molybdenum elements in the sheet steel were not a problem and actually enhanced the bond.

The best results were achieved when the heating cycle was no longer than a few minutes. With a large tool, as in the case of laminate tooling for pressure die-casting, then it would take as long as an hour to get the whole tool up to the bonding temperature.

4. Silicates and Fluorosilicate Enamels

These materials are found in applications as diverse as washing powders to furnace cements. Ground and hydrolysed silicates and fluorosilicates mix readily with water, under pressure and heat, to form a soluble paste. When applied to a metal surface, water evaporates and silicates precipitate out of the solution leaving a layer deposited on the surface capable of withstanding temperatures up to 850^{0}C. Placing the material between two sheets of steel would be difficult due to the fact that evaporation would be very slow and any moisture left in the bond would cause gassing and de-lamination when subjected to the high temperatures of die-casting. To overcome this, it was proposed that the silica solution should be deposited on each of the laminates in turn and allowed to dry thoroughly. Once they were dry, the individual laminates could be stacked together and bolted. The stack would then be placed into a furnace and the temperature ramped up to 850^{0}C to take the silica beyond its glass transition point. On cooling, the silica would fuse and bond the laminates.

What made the process attractive was the wetability of the silica once molten, and also the fact that it did not require completely smooth and flat surfaces to form the bond. The problem associated with this concept was that silica tends to be excellent in compression and very poor in tension. Certainly, the laminates in a stack would be in a compressive state but this would not take into account the nature of the deflection that occurs within the laminate die (Soar & Dickens, 1997). In particular, the bond would have to withstand the thermal shock on the introduction of molten LM24 into the die cavity on each shot.

Work was done to bond laminate stacks with two companies. Fortifix Ltd produce a range of fluorosilicate coating agents which were used to bond laminates as described above. Ferro Enamels Ltd were approached to look at the possibility of using the same process but with the addition of dopants within the solution. This would help match up the diverse thermal expansion rates of the silicates with the steel substrate, and also reduce the brittleness of the completed bond in order to withstand thermal shock in production.

5. *Testing the Bonded Stacks*

Various tests exist for adhesive bonds. For high temperature application, particularly over 250^0C, there are no recognised tests for this application or the material used.
A simple test was devised which would allow the bond for different types of silica to be determined for their effectiveness. Batches of different solutions were mixed up and applied to ten laminates per stack. The solution was allowed to dry, and the laminates in each group of ten were bolted together and placed in a cool furnace (20^0C). The temperature was ramped up to 850^0C over a period of two hours until complete fusion of the silica had occurred to the steel.

On cooling, each of the stacks was pulled gently by hand to establish whether any bonding had occurred between the laminates in the stack. If the stack withstood a gentle pulling, then it was tested for its suitability for die-casting by being heated up to around 500^0C (the maximum temperature that any die should ever reach). After heating, it was plunged into cold water to simulate the effect of water based release agents used in the die-casting industry, and also water cooling, which would pass through the laminate stack in a production tool.

The sudden immersion into water converts some of this heat into steam and may induce the conditions which turn silica from its hard solid state to its soluble/aqueous state. If the silica were to revert back to an aqueous state then the bond would permanently fail.

The normal choice of testing would be to pull the cold bonded stacks apart until failure occurred. This would give a good indication of the effectiveness of that bond but give no indication of the bonds effectiveness when subjected to thermal stress, as well as water/steam. Steam must be a consideration in this experiment due the Wallace 'dunk test' which would be employed by the USCAR consortium later (Appendix II) which uses large amounts of cold water to help induce thermal fatigue in the test samples.

6. *Results*

From the different batches of proprietary solutions which were supplied for testing, it was clear that there were wetability problems with pure silica solutions on to sheet steel. The rougher the surface finish on the sheet steel, the better the wetting. Good wetability was achieved with the fluorosilicate solutions, particularly with the addition of fine ceramic fillers and dopants. After withdrawal from the furnace almost all of the laminate stacks bonded with fluorosilicates showed good adhesion and resisted being 'pulled' apart.

Without exception, all the samples which were bonded failed when subjected to the second stage of the test, which was to heat them then submerge them in cold water. In all cases, the steam penetrated the bond and resulted in severe efflorescence. All the bonds were left with a powdery deposit of the silica with no adhesive properties. Figure 1- 3 show electron microscope slides of the failed joints.

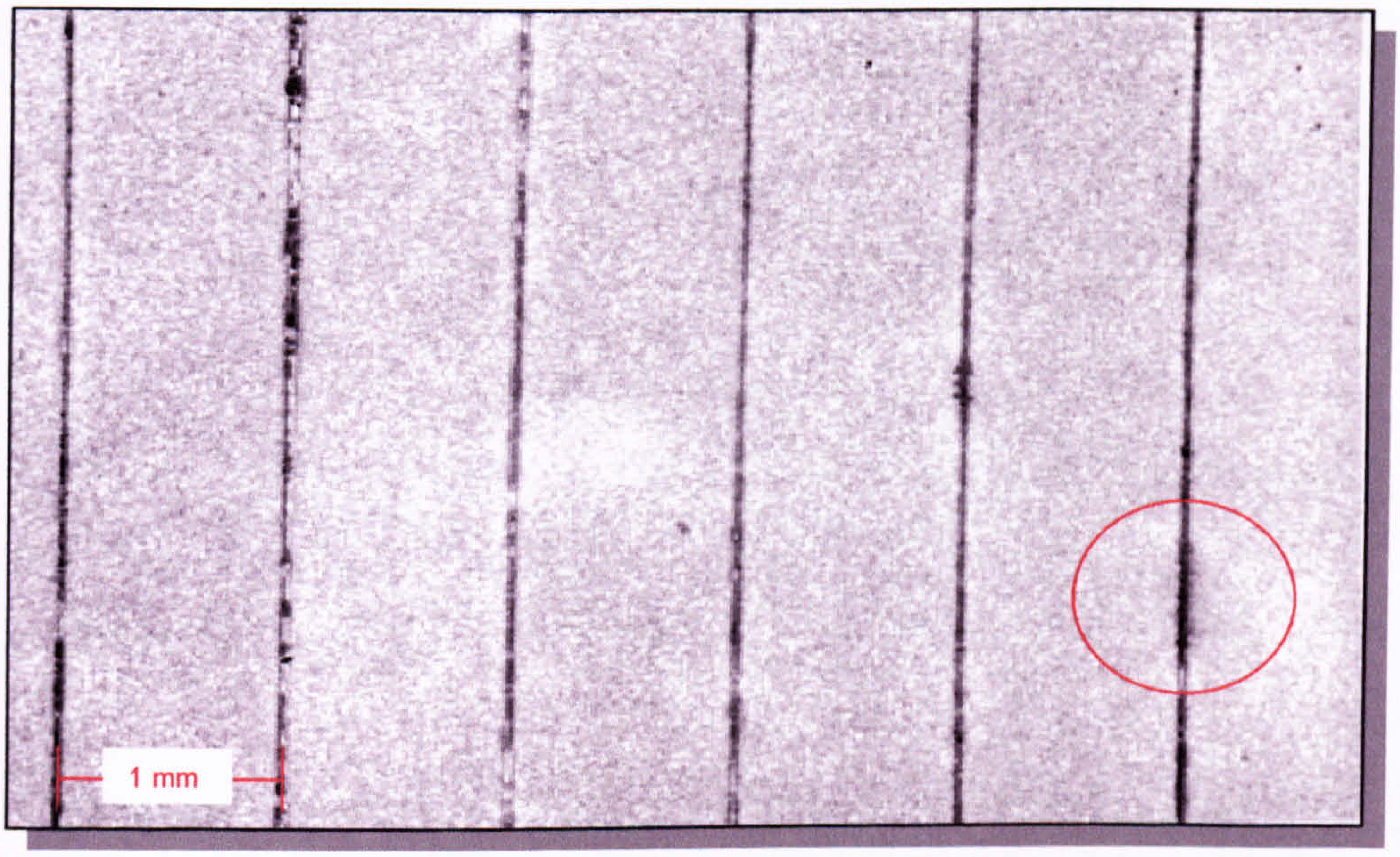

Figure 1. Microstructure of silica bonded 1mm M2 HSS laminates(x15)

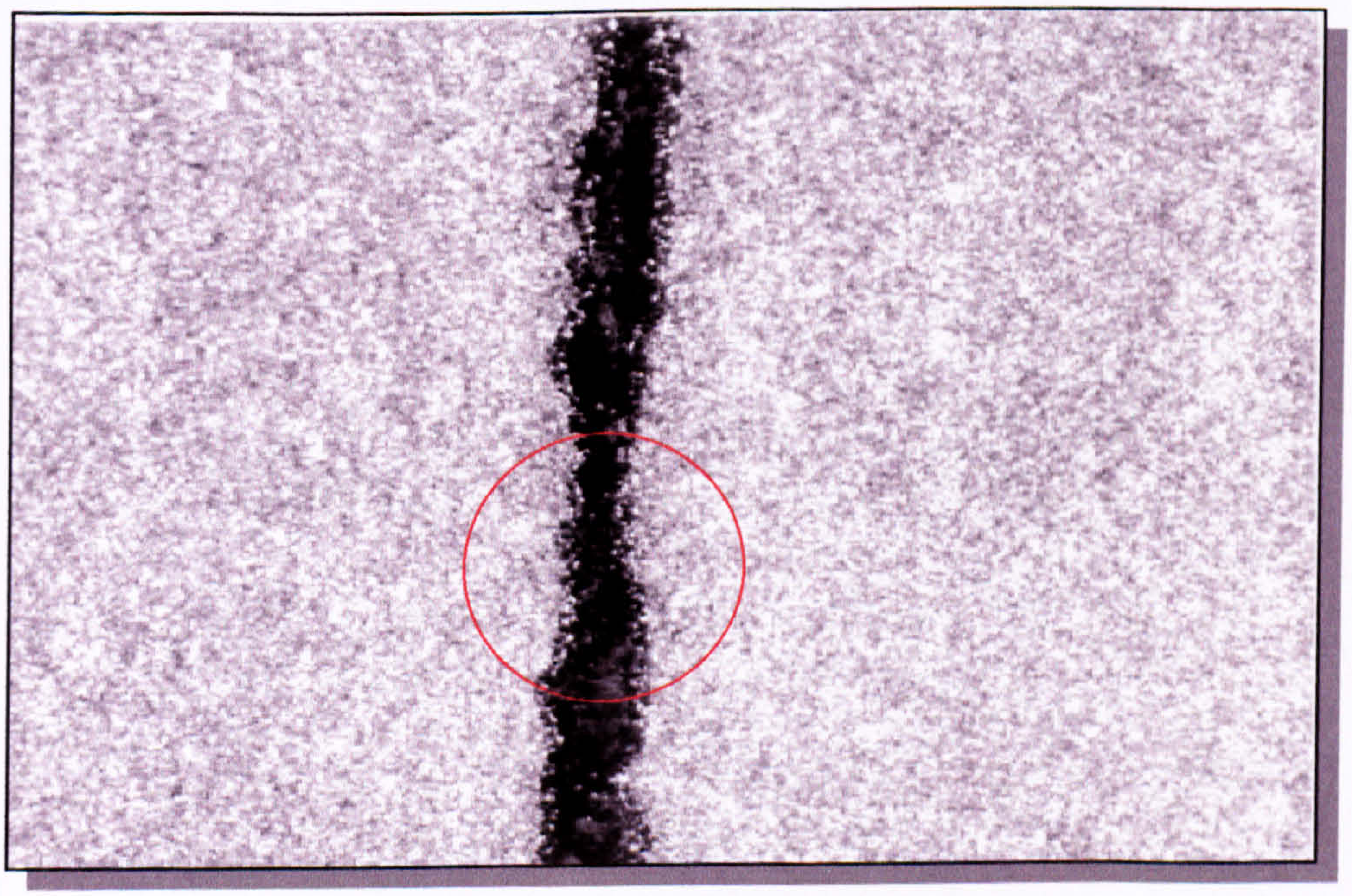

Figure 2. Magnified view between two failed silica bonded laminate joints

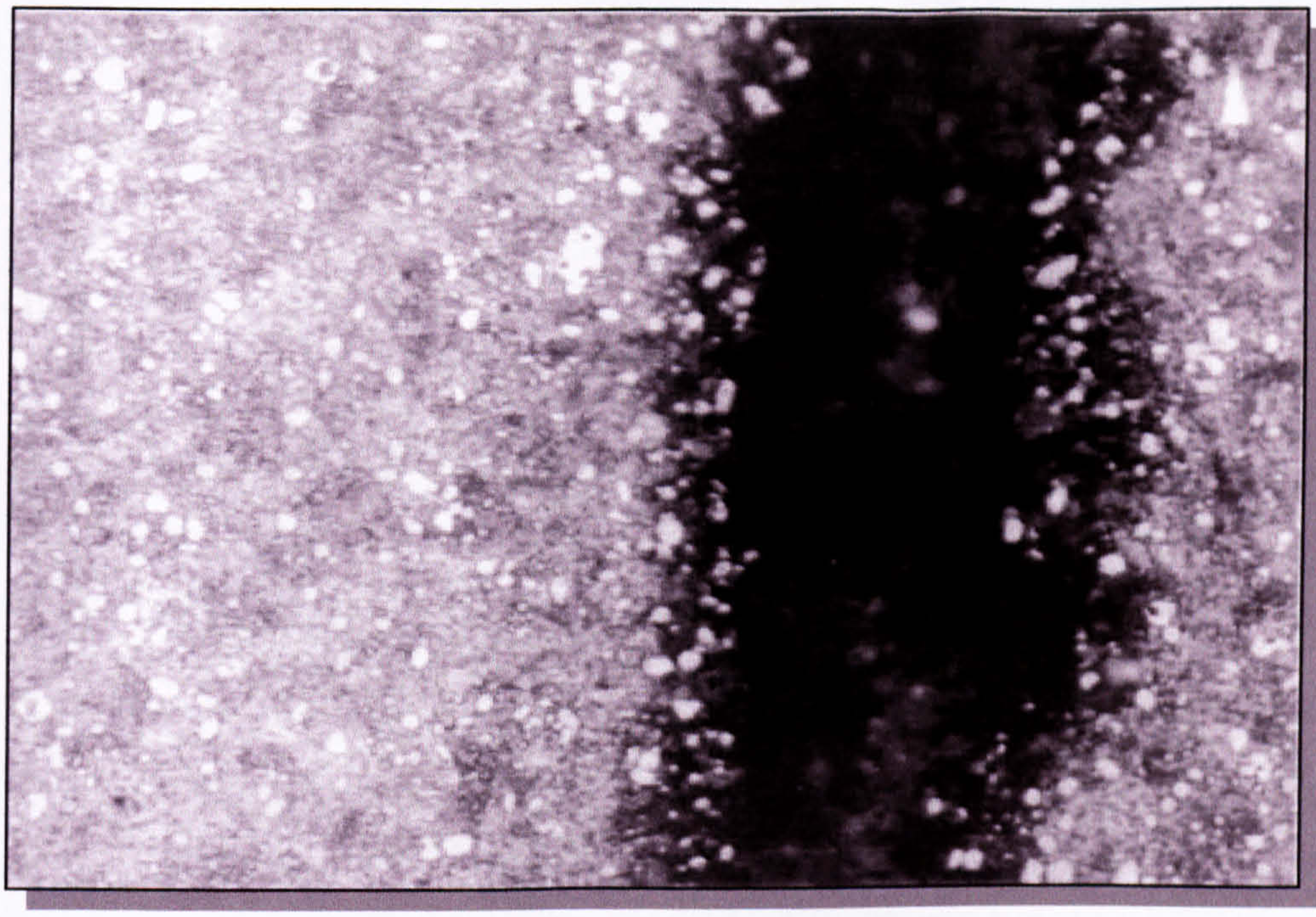

Figure 3. Magnified view of Figure 2 showing no visible silica solution.

7. *Discussion*

At this stage, sodium silicate solutions did not seem suitable for bonding 1mm high alloy tool sheet steel for pressure die-casting applications. Ferro Enamels Ltd, who prepared some of the adhesives, felt that a lot more could be done with the investigation, but there was generally too much doubt as to the effectiveness of the material to warrant further experimentation.

8. *References*

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Appendix II: Progress Report For USCAR Consortium - Developing test samples for the USCAR Project.

1. *Introduction*

The objective of this project was to produce three laminate thermal fatigue testing samples for the USCAR consortium to assess some of the issues which laminate tooling might expect to encounter in the pressure die-casting environment. Each sample would be tested for its resistance to thermal fatigue through continuous thermal cycling, under conditions similar to those found in pressure die-casting. The test was developed by the consortium and is called the 'Wallace Dunk Test'.

Three samples were produced and each sample differed in the way that the laminates of steel in each, were bonded. This project would aid in the assessment of the need for bonding and sealing in laminate structures, as well as test the effectiveness of the different bonding techniques. The first sample had no inter-laminar bond and relied on physical bolting to hold the laminates together. The second was bonded using a proprietary diffusion soldering technique, and the third was bonded using refractory silicates and enamels.

2. *The 'Dunking' Test*

The 'Wallace Dunk' test consisted of dipping samples of stacked laminates in molten aluminium for short cycles and measuring the degree of thermal fatigue that occurred over time. The test measured the degree of thermal cracking that appeared on the surface of the samples when subject to constant thermal cycling or shock. One of the samples, submitted, is shown in Figure 1.

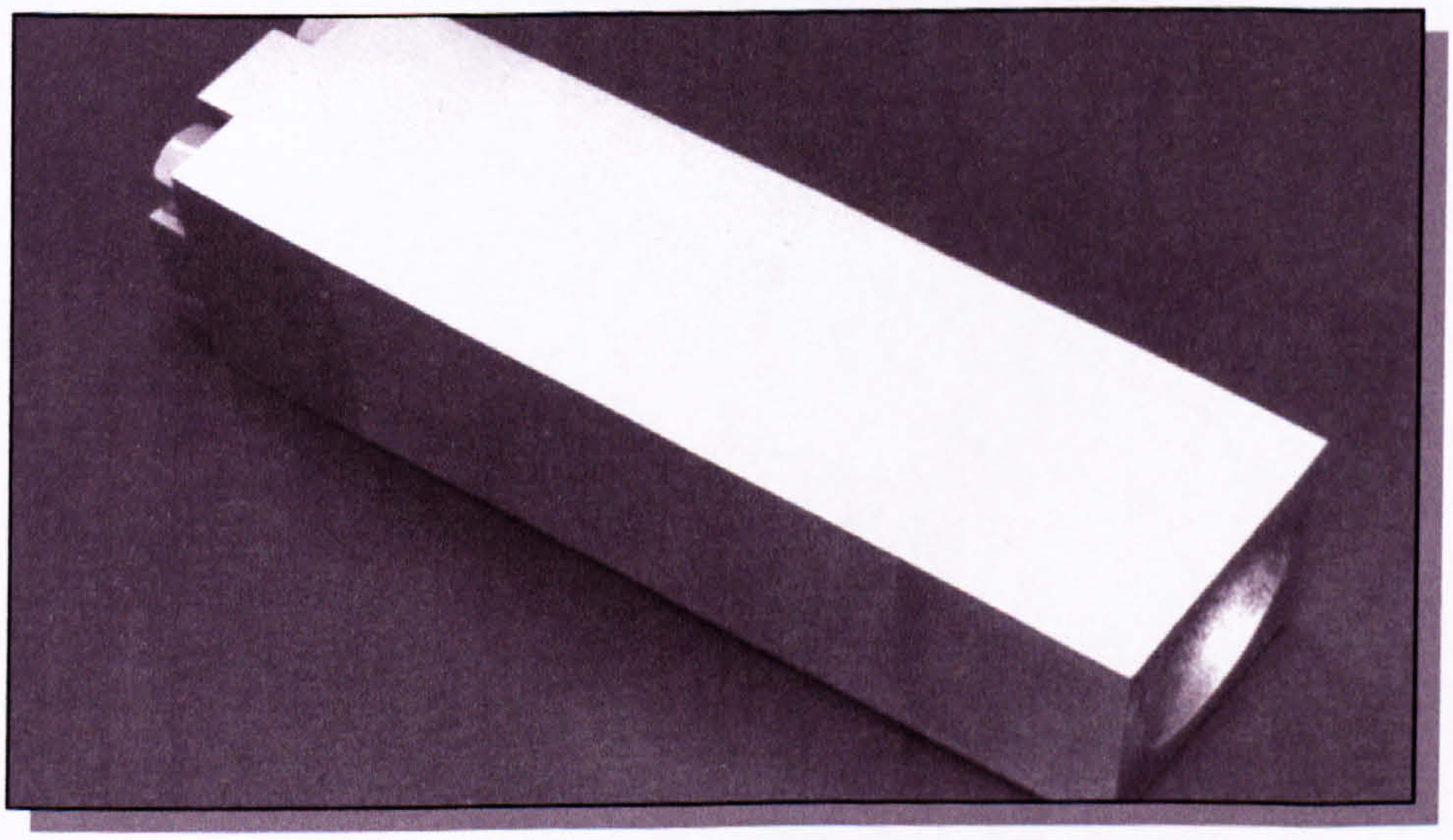


Figure 1. Laminate samples submitted for 'Wallace Dunk' test

Two 50mm thick end-plates constrain the laminates within the measurement zone and are shown in Figure 2.

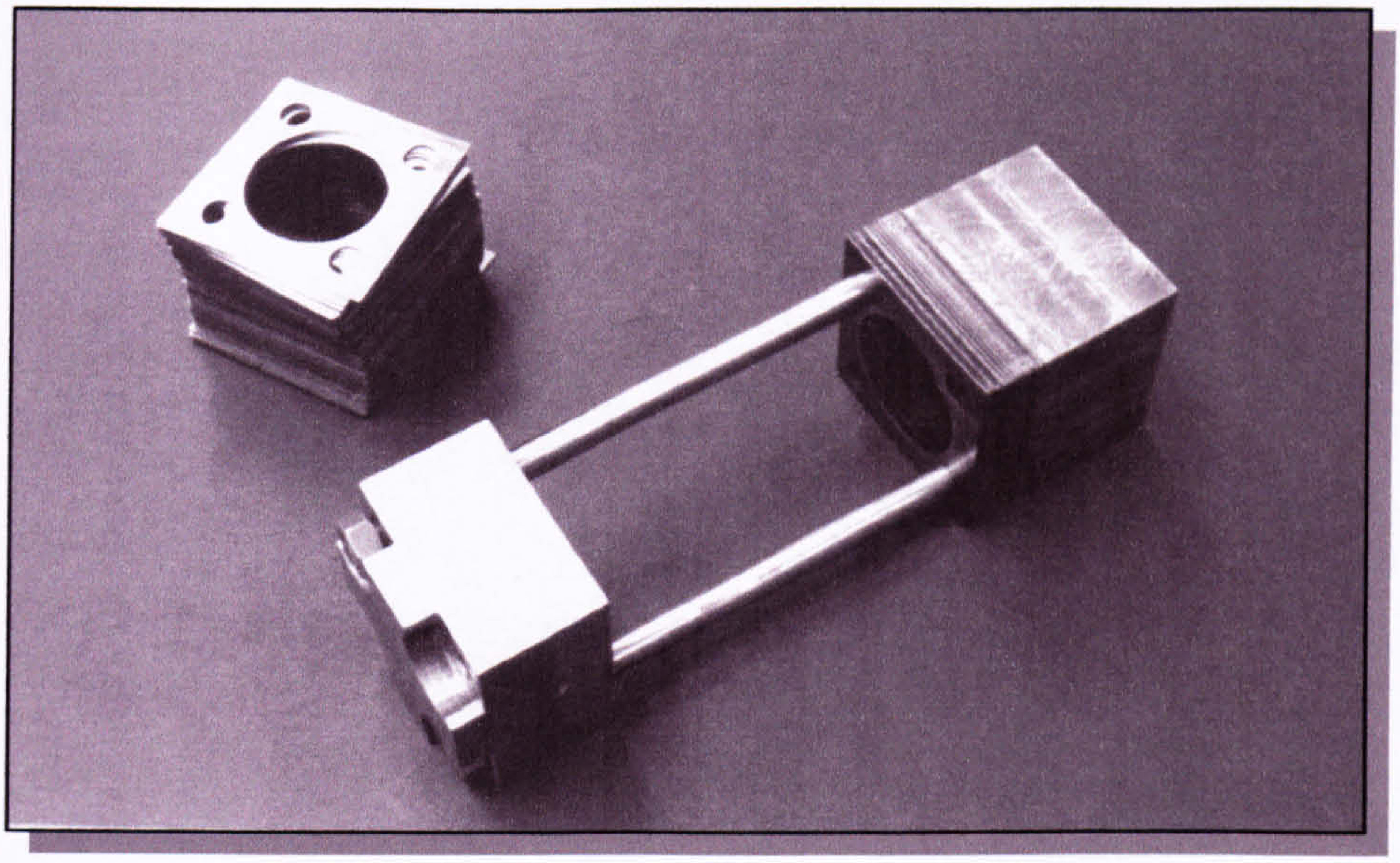


Figure 2 The various elements of the laminate samples

The measurement zone was a section, 75mm long on the four edges, equidistant from each end of the sample. Any cracking pattern was reported as the average 'maximum crack length', and the summation of the squares of the crack length, for each edge of the sample. The more severe the crack pattern, the lower the thermal fatigue resistance of the material. USCAR favoured this test as it closely correlates with behaviour of dies in production.

The test consisted of dipping each sample into molten aluminium alloy, withdrawing it, and then spraying it with lubricant between 'dunks'. Each sample was a 50mm$\times$50mm $\times$177.8mm rectangular, parallel piped, specimen with a 38.1mm diameter blind hole cut into the centre, through which pressurised water was fed to chill it. The four edges had a constant 0.25mm radius which intensified the uniaxial stresses in the measurement zone. The sample was mounted on a rig which allowed it to be submerged in a bath of molten aluminium (LM24) at 732.2^{0}C for 12 seconds, after which it was removed for 22 seconds. During this procedure, water was pumped around the internal chamber in the sample at a rate of 386.4 litres/min. Measurement of cracking was measured after 5000, 10,000 and 15,000 cycles.

3. *Material Choice*

On receiving the material specifications, it became clear that material selection would be critical and by no means straightforward. It was felt that there were three approaches which could be taken. First, was to use a high carbon mild steel such as CS 70 (AISI-SAE 1070). This material was readily available as sheet material and would match the hardness in the specifications.

The attraction of this approach was that it would make a very cheap tool/sample and by using some form of nitriding or surface modification process, a laminate tool would be able to perform as a 'prototype' short run tool. This concept was considered and a thermal fatigue sample was actually produced to look at the viability of this approach, but not submitted to USCAR as the remaining material properties did not match their specifications.

The second approach was to use a low alloy carbon steel with better thermal properties as well as a coefficient of thermal expansion (CTE) close to that specified, such as EN24, 817M40, or martensitic 4140 and 4340. All are readily available 'off-the-shelf' but unlike CS 70, which can be specified in a range of thicknesses down to 0.5mm, the range of low alloy sheet steels available in the UK is limited. A batch of hot rolled 4340 was purchased which required grinding down to 1mm - the thinnest cross section reasonably possible. This material was assessed and samples tested for suitability (Appendix III), but again, it was difficult to match the material properties set by USCAR.

The final option, and the one eventually settled on, was to buy material that suited the specifications of H13 tool steel as closely as possible. Two suppliers were eventually found but they could not deliver within the time frame of the project, and so a compromise was decided upon. High Speed Steel (HSS), such as M1 or M2, is available from various sources, globally, as it is used for cutting tools, knives etc. pressed directly from annealed sheets. Its specification matched H13 very closely with a slight difference in the CTE.

The percentage of alloying elements were very close. The main difference being a slightly higher carbon content in HSS leading to a higher Rockwell C reading of 55-60. It was felt better to over specify than under specify. Embrittlement would be a potential problem with the elevated carbon content during hardening and tempering, but this could be overcome using and evacuated furnace and nitrogen quench. A batch of 1mm M2 HSS was purchased in its annealed state.

4. *Sample Design*

Due to the shape and size constraints of the samples, it was decided to use horizontally stacked laminates. Two end-plates, at the top and bottom of the sample retain the shape of the tool as well as the laminates themselves. The end-plates were 50mm thick so as not to encroach on the measurement zone of the sample. This also allowed sufficient depth to form the tapered thread which was required in the upper end-plate. The end-plates were machined from H13 bar to ensure an equal expansion rate for the stack.

Four studs ran through the length of the sample to retain the laminates. Again, these were machined from H13 bar stock. Due to the physical dimensions of the samples there was a constraint on the maximum diameter of each stud that ran through the length of the sample. If each stud were any wider than 8mm they would have broken through the sides of the sample. If the diameter were any thinner, the bolting force obtainable from the studs would be greatly reduced. As it was, there was some concern that the use of 8mm wide bolts would not give sufficient clamping force to hold the laminates together. On no account could water penetrate between the laminates and enter the melt during 'dunking'.

Sufficient clamping force would be essential, particularly when it came to the bonded samples. Due to the nature of the rolling process, the steel sheet had a rippled surface and any tempering done later would exacerbate this. Unless sufficient force were applied to the laminate stack, there would be gaps between the laminates. The H13 studs had to be tested to ascertain the maximum clamping force they could exert on the laminate stack. Each bolt was first stretched to destruction with a 50 tonne press. This gave an absolute load that the laminates could be compressed, by turning nuts, before the threads snapped.

The average load, that the four nuts gave way on the studs, was 2.65 tonnes. From previous experience it was known that a load of around 10 tonnes would be required on a laminate stack to seal any gaps. The maximum load that could be exerted on the stack was 10.6 tonnes which was, theoretically, sufficient, but left very little margin for error.

On assembly, the laminates were fed down the studs and the lower end-plate positioned last. The four studs protruded through the lower end-plate so that the nuts could be applied to clamp the assembly together. Nuts were applied to the lower end-plate. If they were applied to the upper end-plate they would have interfered with the threaded taper.

5. Production of the Un-bonded Sample

Due to the small inaccuracies that were present in the laser cutting process, an offset of 0.2 mm was defined on the CAD model, for each laminate to be removed after assembly, by spark erosion (if an internal element), or by grinding (if external), to meet the specified finish.

On receipt, the cut laminates were blown with compressed air to remove excess debris, and then 'barrel rolled' in mica for 24 hours to remove burrs and scale. Two nuts on each stud were used as a locking mechanism and all internal and external faces were finished, as shown previously in Figure 1.

To ensure the un-bonded sample would not leak during the 'dunk' test, an adapter was made which allowed the sample to be pressurised internally, so that leaks could be detected between the laminates. The unit is shown in Figure 3.

Leaks occurred particularly where the laminates abutted the end plates, and also from the holes in the endplates that held the studs. In the un-bonded sample, for this particular test, the pressure offered by the studs would be inadequate in preventing water entering the melt in the 'dunk' test.

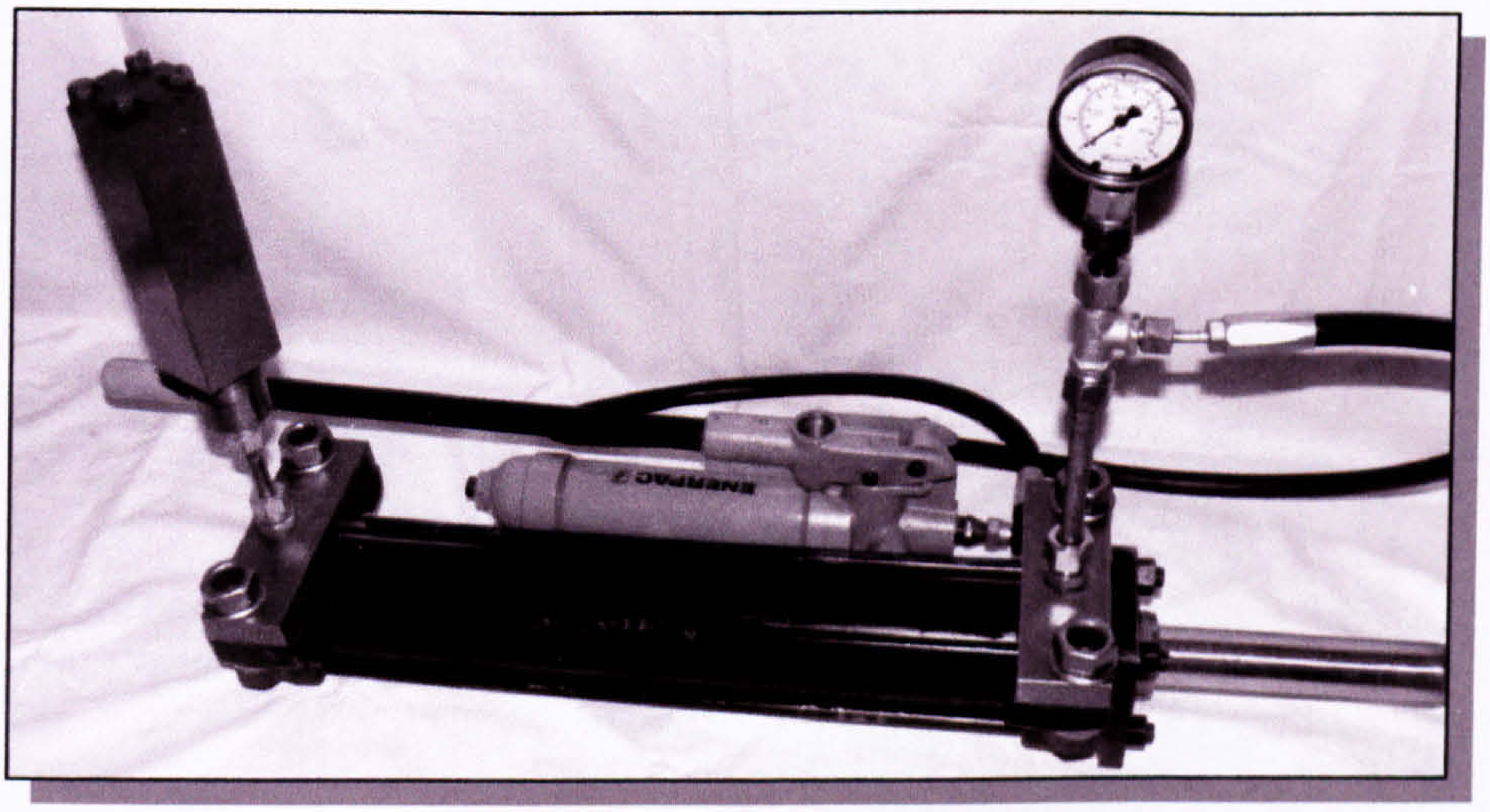


Figure 3. Pressure testing rig to test samples for leaks

6. Production of the Silica Bonded Sample

The second approach used high temperature adhesives. Some of this work is covered in Appendix I. Extensive work had been done with high temperature organic/epoxy resins for use in laminate injection moulding tools, but these adhesives would not work at the elevated temperatures found in die-cast tooling.

The laminate stack was assembled, as in the un-bonded sample, with no adhesive. The sample was then mounted on the pressure test rig and the internal void of the sample filled with a solution of sodium silicate. By pressurising the internal chamber of the sample, to overcome the viscosity of the solution, it was possible to force silica solution between the laminates and fill any voids. The rig was set up so that a second piston would act on a slave cylinder to the primary hydraulic piston. Pressure would then be transmitted to the silicate solution on the other side of the slave cylinder which, in turn, would force sodium silicate solution into the internal chamber as shown in Figure 4.

In this way, it was possible to generate pressures in excess of 6MPa. The sample tool was pressurised for two hours at 5.8 Mpa, during which time the solution was actually forced right through the stack. The excess was poured off and the sodium silicate cured for three hours, at 75^0C, to drive off the water in the solution. The sample was then fired to 800^0C to fuse the silica to the laminates in the stack and bond them.

To test the effectiveness of the seal, the sample was again mounted on the pressure test rig. As in the sample before, gaps had appeared in the laminates that allowed the passage of water. The sample was also heated in the presence of water to check the solubility of the silica at elevated temperatures. The bond failed as the silica reverted back to its aqueous state.

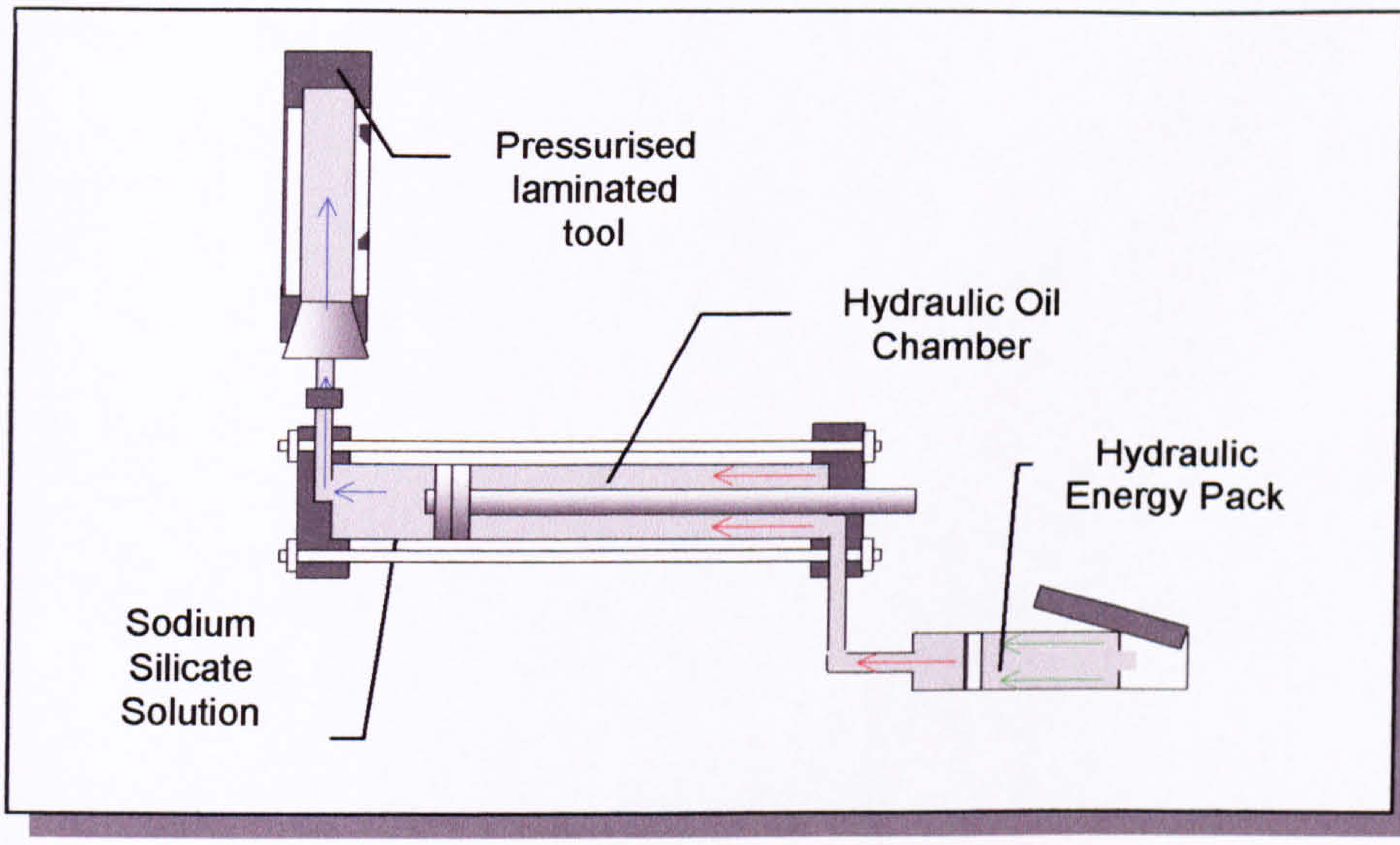


Figure 4. Schematic for method of sealing leaks in the test samples

7. *Production of the Diffusion Soldered Sample*

Where laminate tooling is applied to pressure die-cast applications, the pressures and temperatures involved would sometimes be too great for bolting alone. Where up-stands and fine internal detail occur, the laminates in these areas do not receive the full clamping pressure that bolts offer to the main body of the tool.
Nakagawa *et al* (1985) addressed this issue using a compression forging technique. In this process, the tool was heated under moderate pressure up to a point just below its liquidus phase. The tool was removed from the furnace and subjected to a large force for ten seconds in an oxidising environment. The tool was then placed back in the furnace and allowed to cool over 24 hours. In trials, this process gave an almost perfect fusion of each laminate with as little as 2% reduction in overall length.

For the USCAR project, a joint venture was undertaken to modify a promising technique developed by GEC - Marconi Ltd. Much of the detail in the production of the samples is reproduced in the author's joint paper (Bocking *et al*, 1997), at the end of this thesis.

The process is a combination of the soldering and diffusion bonding process called diffusion soldering (Humpston *et al*, 1993). The process offers the benefits of the low temperatures achieved in soldering, with the excellent bonds achieved with diffusion bonding.

The production of the sample differed from the previous two samples, primarily due to the greater compressive loads required to bond the laminates completely. So effective was the process at bonding and sealing the laminates, that the studs used in the previous two samples were not required. The diffusion soldering process requires a pressure of 10MPa on the stack to bond it effectively. Converting 10.6 tonnes (the maximum load the studs could exert) on an individual laminate area of 2601mm^2 (51×51mm), gives only 0.4Mpa working on the stack.

To ensure that a constant pressure of 10 MPa was achieved on the laminate stack, the assembly was mounted and clamped into a secondary jig that enabled the force on the laminates to be increased beyond 10Mpa. This is shown in the schematic in Figure 5:

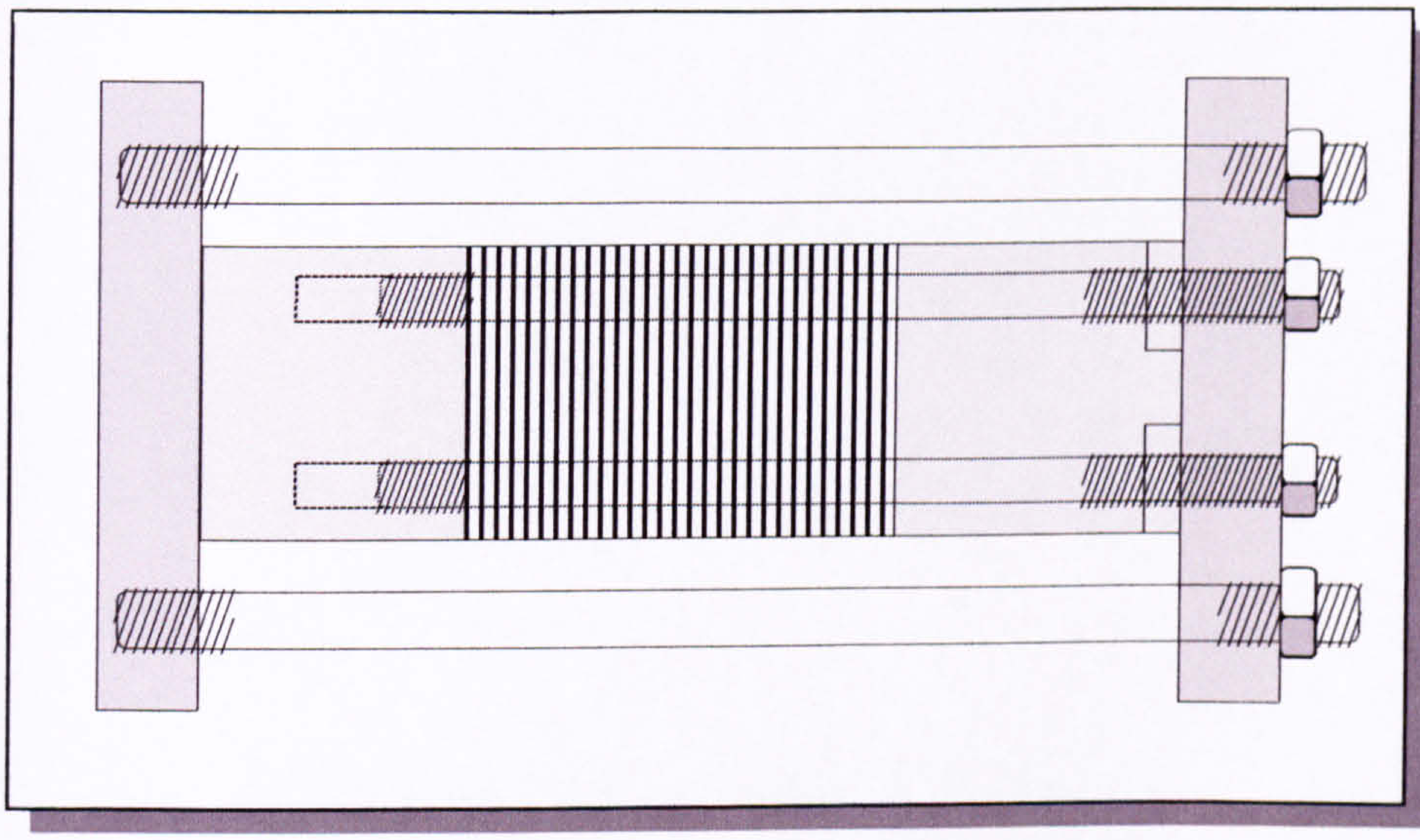


Figure 5. Schematic of secondary clamping jig

Prior to clamping, the laminates which made up the sample were first electroplated with silver, and then tin. The entire assembly was treated, as described in the author's paper, and the finished sample is shown in Figure 6.

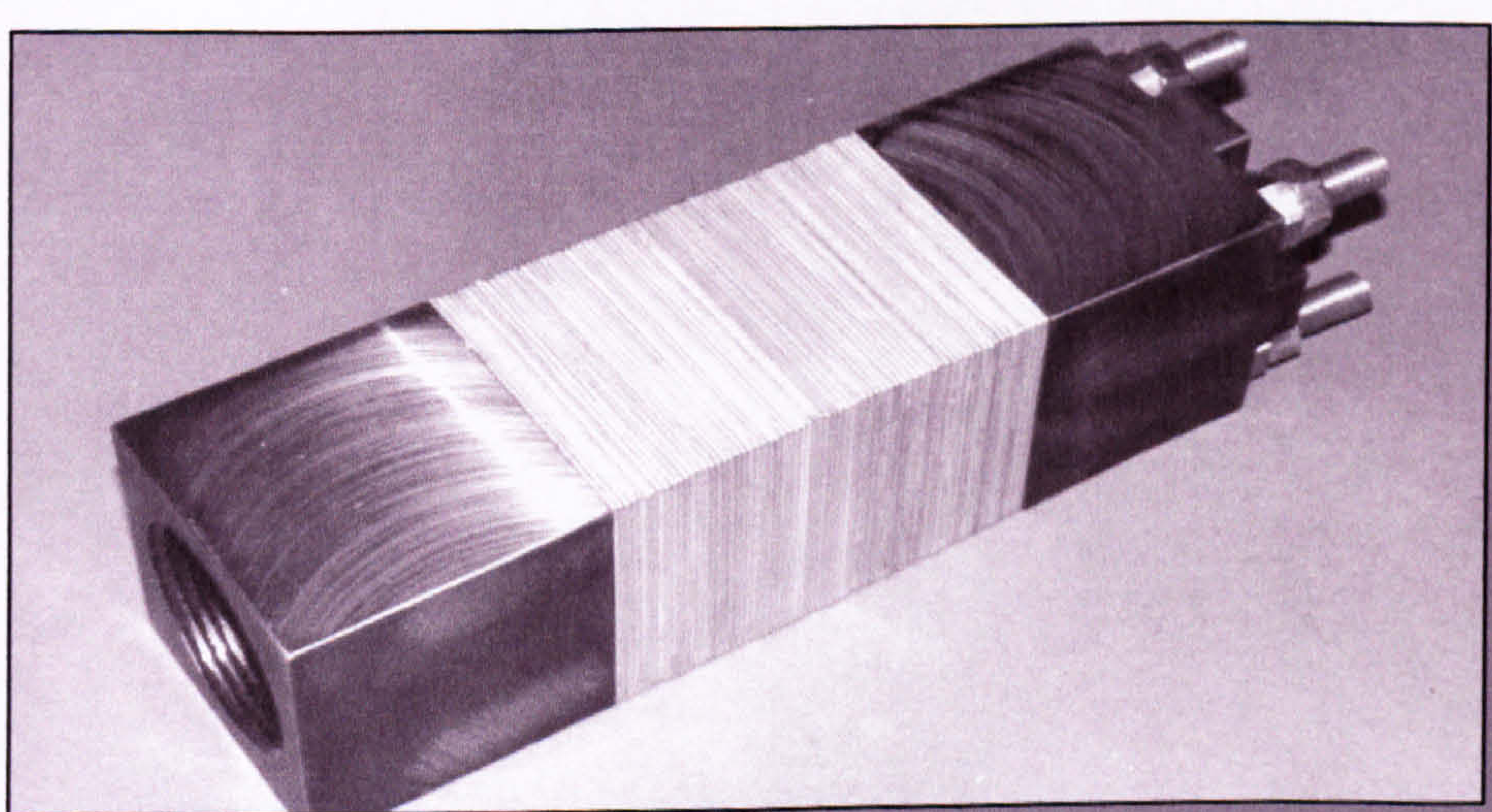


Figure 6. Completed diffusion soldered sample for USCAR

8. Conclusions

The first sample was constructed with no inter-laminar bonding. However, due to the design constraints on the thermal fatigue samples, a large enough clamping force could not be achieved and leaks were observed. The second sample was an attempt to bond the laminates using a sodium silicate high temperature adhesive. The sample was tested for premature failure and the sample did not withstand this process.

The third was submitted to USCAR for the 'Wallace dunk' test. The sample withstood continuous thermal cycling for a few hundred shots before the joints began to break down in certain places and the experiment had to be terminated due to the risk of water coming into contact with molten aluminium in the furnace. It should be noted that USCAR were looking for alternative Rapid Tooling techniques which could directly substitute existing solid H13 dies for production tooling, where thousands of parts are required. A fourth sample piece was produced with a thick copper liner inside the laminate stack to retain the pressurised water.

9. References

Humpston, G., Jacobson, D.M. and Shanga, S.P.S. (1993) **Diffusion Soldering: A New Low Temperature Process for Joining Carat Gold Jewellery,** *Gold Bulletin* 26, no. 3, pp 90-104.

Nakagawa, T., Kuneida, M. and Liu, S.D. (1985) **Laser Cut Sheet Forming Dies,** *Proc. from the 25th International MTDR Conference,* April 1985, pp 505-510.

Appendix III: Internal Report - Appraisal of sheet material suitable for HPDC applications.

1. Abstract

The objective of this study was to identify suitable sheet material for the production of laminate pressure die-cast tooling, as well as samples for thermal fatigue testing by the USCAR consortium. These samples would be subsequently tested for their resistance to thermal fatigue failure at elevated die-casting temperatures.

2. Introduction

The USCAR consortium submitted specifications for tool steel considered suitable for pressure die-casting. These are shown in Table 1.

Material Hardness	Min 36 Rockwell C Max. 45 Rockwell C
Thermal Conductivity	16.5 BTU/FT.H. ^{0}F @ 420^{0}F (215^{0}C)
Thermal Expansion	Max. value 6.4 mic.in/in @ 400^{0}F 11.5 mic.m/m @ 204^{0}C Max. value 7.3 mic.in/in @ 1200^{0}F 13.1 mic.m/m @ 649^{0}C
Machinability	Comparable to H-13 at 42R_C
Microfinish	Max. value = 120 mic.in (0.3 μm)
Heat Checking	No cracks greater than 0.020" (0.5 mm)

Table 1. Specification for USCAR samples

3. CS70 High Carbon Strip Steel

The most readily available cold rolled sheet metal in the UK, at this time, was "CSxx grade high carbon strip steel". This material had been successfully used for the laminate injection mould tool. The CS classification is followed by a figure that represents the percentage carbon present in the steel. To achieve the specified hardness for the material, samples of CS70 strip were assessed (0.7% Carbon), the equivalent AISI-SAE grade was 1070. This was flattened and hardened to 415/435VPN or 42/43 Rockwell C. The coefficient of thermal expansion for this material was 11.499mic.m/m@ 204^{0}C and 13.29mic.m/m@1649^{0}C which just fell into the specified range.

It was important to establish what effect molten aluminium would have on the hardness of the metal sheet. To test this, 50×50mm samples were cut from the sheet and submerged or 'dunked' in molten aluminium for ten seconds. This represented a worst case scenario which the steel could be subjected to when in use. The results of this test are shown in Table 2:

	Individual 10 Kg VPN Readings				VPN	Rockwell C
1st Batch	308	333	308	306	**318**	**32**
2nd Batch	265	265	265	262	**264**	**25**

Table 2. Results of submersion test

If the CS70 laminates were allowed to heat up to the maximum operating temperature of the tool they would anneal to well below the specified hardness range. The average temperature within a die-cast tool fell below the annealing temperature of CS70, but it was difficult to know what may happen to the steel if hot-spots were to occur within the tool.

4. EN24 and 4140/4340 Low Alloy Steels

To overcome the effects of the heat generated in the die-casting process, suitable steel sheets would require alloying elements to provide stiffness. The carbon in the CS70 was lost through carburization during the rapid heating and quenching of the samples. Three grades of medium alloy grade steel sheet predominate this grade of steel. These are EN24, 4140 and 4340 grades. Their compositions are shown in Table 3:

	C	Mn	Si	S	P	Cr	Mo	Ni
EN24/ 817M40	0.36-0.44	0.45-0.70	0.10-0.35	0.040 max.	0.040 max.	1.00-1.40	0.20-0.35	1.30-1.70
4140	0.36-0.44	0.45-0.70	0.10-0.35	0.040 max	0.040 max	0.50 or 0.95	0.12 or 0.20	1.30-1.70
4340	0.36-0.44	0.45-0.70	0.10-0.35	0.040 max	0.040 max	0.50 or 0.80	0.25	1.80

Table 3. Composition of test samples

Though it appears as if there was a slight difference in the composition of the steels, all three grades are similar in both mechanical and physical properties to EN24. For this reason it was decided to purchase samples of 1mm thick EN24 (based on availability) as a representative of how low alloy sheet steels behave at elevated temperatures. The sheets were then hardened/tempered, as recommended for EN24, using standard furnace and salt bath quench which should have brought them up to the specified hardness.

The hardened sheets of EN24 were then divided up into ten samples. Five samples were then dunked for ten seconds in molten aluminium and allowed to cool at room temperature. All were then subjected to 10 Kg Vickers hardness testing so that the heated samples and the non-heated samples could be compared. The results are shown in Table 4:

Dunked Samples Sample No.	Dimensions mm	Vickers Hardness.
1	303×303	202
2	303×303	202
3	304×304	201
4	302×302	202
5	295×295	213

Untreated Samples Sample No.	Dimensions mm	Vickers Hardness.
6	305×305	199
7	293×293	216
8	303×303	202
9	297×297	210
10	293×293	218

Table 4. Hardness readings of test samples

Overall both the dunked and untreated samples were too soft. An average hardness of around 21 RockwellC (Rc) was achieved, which fell well below the 36 Rc specified. These readings were actually lower than the CS70 readings. The samples were showing an excessive amount of scale build up on their surface which indicated a possible migration of the carbon out of the sheet steel as it reacts with atmospheric gasses during the heating process.

5. *M2 High Speed Steel*

Samples were acquired of 1mm thick M2 grade High Speed Steel that had the closest composition to the standard die-casting H13 hot work tool steel that USCAR were implying would meet the specifications. M2 is commonly used for the cutting blades of blanking tools and for surgical steel cutting tools.

There was concern that the increased amount of carbon present in M2 (over H13) would make the material too hard and possibly, too brittle. M2 HSS steels are commonly tempered to a range of 50-75 Rc, which would fall outside the constraints of the study. In addition, the high hardening temperatures of M2 (1200^{0}C) could have had a strong carburizing effect on the thin laminates, leaving them both distorted, thinner and too soft.

The M2 was delivered in its fully annealed state and was hardened and tempered. This was difficult as, at this time, there was no access to an evacuated furnace or nitrogen quench. To perform a normal hardening procedure (i.e. furnace then oil quench) on thin sheet steel would have the same affect as submersion in molten aluminium alloy, which had been used to test for annealing in the previous samples. Consultation (Carlisle's Ltd) confirmed the all thin sheet steel suffer from an excessive migration of carbon, in the form of scale, from the steel substrate during the standard hardening process. They recommended the use of either very low carbon steels or advanced hardening/tempering processes to prevent migration. However, to complete the study, tests with full hardening and tempering in oil (cyanide salts were not available) were performed in the following sequence:

- Place the laminates into the furnace and hold at 500^{0}C for 20 minutes.
- Raise the furnace temperature, over one hour, to 900^{0}C.
- Hold at 900^{0}c for 15 - 20 minutes.
- Raise to 1100^{0}C and hold for no longer than 15 minutes.
- Oil quench.

The samples were shot blasted to remove the scaling from each sample and finally ground with "wet & dry" to get a Vickers hardness reading, using a 10Kg weight. There was such heavy carburization that almost all the carbon was being lost due to the high temperatures and the reaction with the surrounding atmosphere. Average Vickers hardness figures of 205-215 were recorded. These figures were too low to convert to Rc, but would be somewhere around 20-21 Rc.

To harden all the laminates in an inert environment was not an option at this time, but some investigation revealed a process for 'half-hardening' steels for situations such as this. The temperature in the furnace was ramped to 500^{0}C and then raised slowly to 850^{0}C. The laminates were quickly removed and quenched in oil. The result was that little carburization occurred (as well as little distortion) due to the lower temperatures in the furnace. This technique did achieve the desired Rc figures reasonably consistently. Hardness figures for samples are shown in Table 5.

Sample A	47 Rc 48 Rc 51 Rc 51 Rc 50 Rc 49 Rc 47 Rc
Sample B	35 Rc 48 Rc 50 Rc 42 Rc 44 Rc 39 Rc

Table 5. Mean hardness figures for test samples

6. *Conclusions*

Though M2 HSS was shown to meet the specifications for hardness, there were still doubts over the effect the high carbon content of this steel would have. Die-casting tool steels require a degree of ductility whilst retaining their overall stiffness. This was the reason that H13 had such a low carbon content and high levels of alloying agents which would give it the hardness at high temperature (such as tungsten, vanadium and chromium) which it needs.

For the development of laminate tooling for pressure die-casting it was realised that a supplier of H13 sheet steel had to be located who could supply large enough quantities of the desired thickness. In addition, though the half-hardening process used on the M2 sheet steel prevented excessive migration of carbon out of the substrate its use did not give consistent results. Future samples would have to be hardened using vacuum furnace and nitrogen quench to prevent this.

Appendix IV: Internal Report - Off-line deflection testing apparatus.

1. Introduction

A direct or 'on-line' study of deflection within a laminate pressure die-cast die had proved impossible within the bounds of this thesis. Methods do exist to observe effects within a die during casting but they can be misleading. The use of x-ray or ultrasound techniques are used to analyse flow within a die cavity but, within the scope of this project they are too costly and cannot been used with the die mounted on the die-casting machine.

2. Deflection Testing Apparatus

One solution was a physical simulation on a scaled down test rig of a die-cast die to observe the effects of the variables as they acted on a laminate up-stand. It was critical that the velocity, gate size, and all chamber dimensions were duplicated carefully so that the observed deflection was a true representative.

In order to scale down the actual die-casting process, a suitable substitute for molten aluminium alloy had to be found. The key lay in using a fluid that, at room, temperature would behave as molten aluminium, so that by removing the heat from the model, all the other elements could be measured accurately by a variety of means.

Previous work (ASM- Metals Handbook) to establish the viscosity of aluminium (at the centre of its volume) has shown it to be comparable to water. For this reason, tests for flow characteristics and gating design, within a die, are sometimes performed using water. However this can be misleading, as viscosity plays only a small part in describing how molten alloys flow in the die. In metal-casting the term Fluidity is used to take into account, not only the alloy's viscosity, but also it's surface tension. The surface tension of a molten alloy passing into a die cavity may fluctuate due to the interaction of the molten alloy with oxides and impurities that are picked up along the way. In addition, as the molten alloy flows through the die it is cooling rapidly and this also affects the surface tension by converting the alloy at the surface from a smooth flowing liquid to a granular or semi-solid 'slush'.

Two experts in the field were consulted, Dr John Birch of the Zinc and Die-casters Association (ZADCA) and Professor Catalin Poppa, a Materials Science expert visiting from Romania. Both knew of examples where hydraulic fluid had been successfully substituted but the exact viscosity still had to be established.

A further problem was that 66 MPa (maximum pressure exerted by the EMB machine) was too high a pressure to apply to a small laboratory test rig. To simulate a fluid entering a die chamber (as a burst of flow) required an accumulator in which pre-

pressurised fluid could be released at a constant rate that matched the outlet velocity of the die-casting machine. It was not practical to pressurise an accumulator to this level on a laboratory bench, so the solution was to scale down the problem.

In a static loaded system, conventional elastic displacement calculations allow for the deflection angle $\boldsymbol{\emptyset}$ to be worked out by incorporating $\boldsymbol{E}$ (the modulus of elasticity) and $\boldsymbol{I}$ (the second moment of area or inertia).

$$\emptyset = {}^{M}/_{EI} \; [\text{where } I = bh^{3}/_{12}]$$

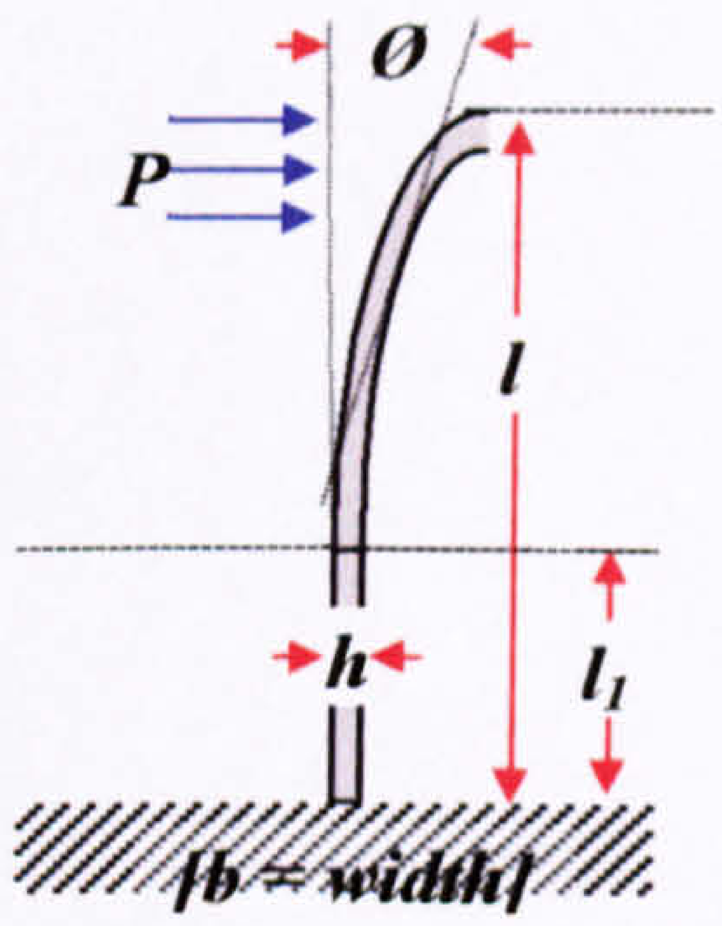
Expanding this equation reveals a relationship between the two constants- pressure $\boldsymbol{P}$ and thickness $\boldsymbol{h}$ where : -

$$\emptyset = {}^{M}/_{EI} \; [\text{where } I = bh^{3}/_{12}]$$

$$M = F(l + {}^{l-l_1}/_{2})$$

$$F = p\,b\,(l - l_1)$$

$$\emptyset = \frac{12\,p\,\cancel{b}\,(l - l_1)\,(l + {}^{l-l_1}/2)}{E\,\cancel{b}\,h^3}$$



By assuming $\boldsymbol{\emptyset}$ to be constant, so ${}^{P}/_{h3}$ is constant. By scaling down the problem by a factor of two the following result emerges:

$$h^{1}(\text{width}) = {}^{h}/_{2} \quad \text{and} \quad p^{1}(\text{pressure}) = {}^{P}/_{8}$$

This was an interesting relationship as it implies that for every halving of the laminate thickness the same deflection can be observed using an eighth of the pressure.

This relationship could be used for almost any sheet steel. This is because the Young's modulus rarely differs from one type of steel to another. Properties such as hardness would make the yield strengths differ greatly, but this need not be taken into account because measurements would be made on deflection before yield could occur.

Applying this to a 1mm laminate in the EMB machine meant that a test rig could be used to observe the effect on a 0.5mm thick laminate using a reduction in pressure of the order of eight (i.e. 7.7 MPa instead of 66 MPa).

By scaling down the laminate and the pressure, all the other elements of the apparatus had to be equally scaled. This included the cavity in the chamber, and more importantly, the gate size as this would directly influence the velocity. The type of gate would be a 'fan' gate. There would be three interchangeable gate designs made, so that the difference which they made to the turbulence and velocity of the pressurised fluid in the apparatus could be compared to the effects on the cast parts in the actual die.

The final adaptation to the test apparatus would be the inclusion of a variable damper behind the laminate up-stand. As mentioned earlier, as the fluid strikes the back of the die chamber, shock waves would be set in motion that would cause the laminate to oscillate. This would be exacerbated by the effect of turbulence created as the fluid flowed around the up-stand.

It was expected that the 0.5mm laminates would have a different resonating frequency than a 1.0mm laminate, but this would have taken another experiment to find out by how much. To overcome this a projection or damper was included in the chamber behind the up-stand to reduce the influence of turbulence.

The design of the test apparatus was shown in Figure 1 and 2 (at the end of this report). The damper can be seen as a projection to the right of the up-stand. The dotted outline denotes an aluminium frame which would be needed to retain the two sheets of 25mm toughened optical 'Perspex' (seen in cross section on the right), which would allow direct measurement of the deflection as it occurred.

The design also incorporated two extractable t-bars so that the laminate height could be adjusted. This also allowed for the removal of the up-stand assembly so that, if time permitted, it could be replaced with an arrangement of ten bolted laminates which could be orientated 'end-on' to the incoming flow of hydraulic fluid.

If the orientation of the laminates was changed then a viewing port would also be needed in the rear of the apparatus through which the deflection could be observed and measured.

3. *Measuring the Degree of Deflection & Ingress*

There were two ways in which deflection, and therefore ingress, could be analysed and measured. The first was to record the entire event on film or video. This would give a clear picture of what was happening to the laminate as the fluid hit it and also show the more subtle effects of turbulence, resonance and ingress. The second method was to use a transducer that would convert the physical deflection at the point of ingress into a direct measurement. Ideally this experiment would incorporate both.

3.1 High Speed Cameras

Estimates based on fill times in actual dies suggest 10 milliseconds or lower. The time taken for the laminate to fully deflect and equalise would be even less. Whether the event was recorded digitally, or with conventional high speed film, to get a clear picture of the maximum deflection would require a frame speed of between 1000-10,000pps (photographs per second) or 1 kHz-10 kHz.

The maximum that scientific cameras will run to is 10,000pps but this is considered an extreme and can be expensive (£1000/day). The solution would have been to hire (£200 per day) or borrow (Thorn & Alcam ltd) a camera working to 2000pps (2 kHz), and combine it with a strobe light working at 4-6,000pps (4-6 kHz). Using this technique would give two or three clear strobe images appearing on each frame of the film or video. At the very least a measurement of the exact time the chamber took to fill would be possible.

3.2 Charged Couple Device Arrays (CCD)

An alternative was to use a linear CCD array. This would require a light source behind the apparatus so that a shadow would be cast, onto the array, on the other side of the Perspex. The array could then pick up the movement of the shadow. Though the sampling frequencies were high with these devices the limitation would be the diffusion and potential refraction of the shadow as it passed through the viewing window.

3.3 Laser Reflection

By polishing the laminate up-stand it would be possible to direct a laser beam onto a specific part of the measurand. The beam would enter the chamber at the rear of the apparatus through the viewing window mentioned above. As the measurand deflected, the beam would move and could be measured by directing the beam onto photographic paper. By pre-calibrating the deflection effect on the beam as the laminate was bent, a direct measurement would be possible. This would overcome any defraction of the beam as it responded to movement of the laminate. The limitation to this technique was the change in defraction as the fluid enveloped the laminate and crossed the path of the beam. This would bias the results.

3.4 Strain Gauges

Strain gauges offer the benefits of low profile, ease of use and the ability to squeeze them into places that cannot be visualised easily. Though good contact and calibration are vital to success they are quite simple to set up and run. As the signal emitted is analogue then the sampling rate does not become a problem, particularly if used with a data capture oscilloscope.

The main concerns with their use was, first, the velocity of the fluid passing over it may dislodge the device and, second, the pressure generated in the chamber may adversely affect the results in an unknown manner. Strain gauges are not sensitive to movement at a particular point and can give an average reading for deflection over the laminates entire length.

3.5 L.V.D.T.'s

LVDT's would suffer the same problems that have, previously, been stated for transducers, except they would offer a few advantages.

1. They are easy to set up and install.
2. Displacement could be measured directly with no calibration.
3. Displacement is linear and correlates exactly with the movement of the measurand.

4. An LVDT unit would also act as the damper to reduce turbulence in the fluid.
5. It only measures that part of the measurand to which it is attached.

There was concern that there would be an effect on the deflection of the laminate as the LVDT would be physically attached to the laminate.

It was felt that a combined reading from a high speed video with a strobe back-up and an LDTV device would give an excellent indication of how deflection was occurring in the die.

4. Conclusions

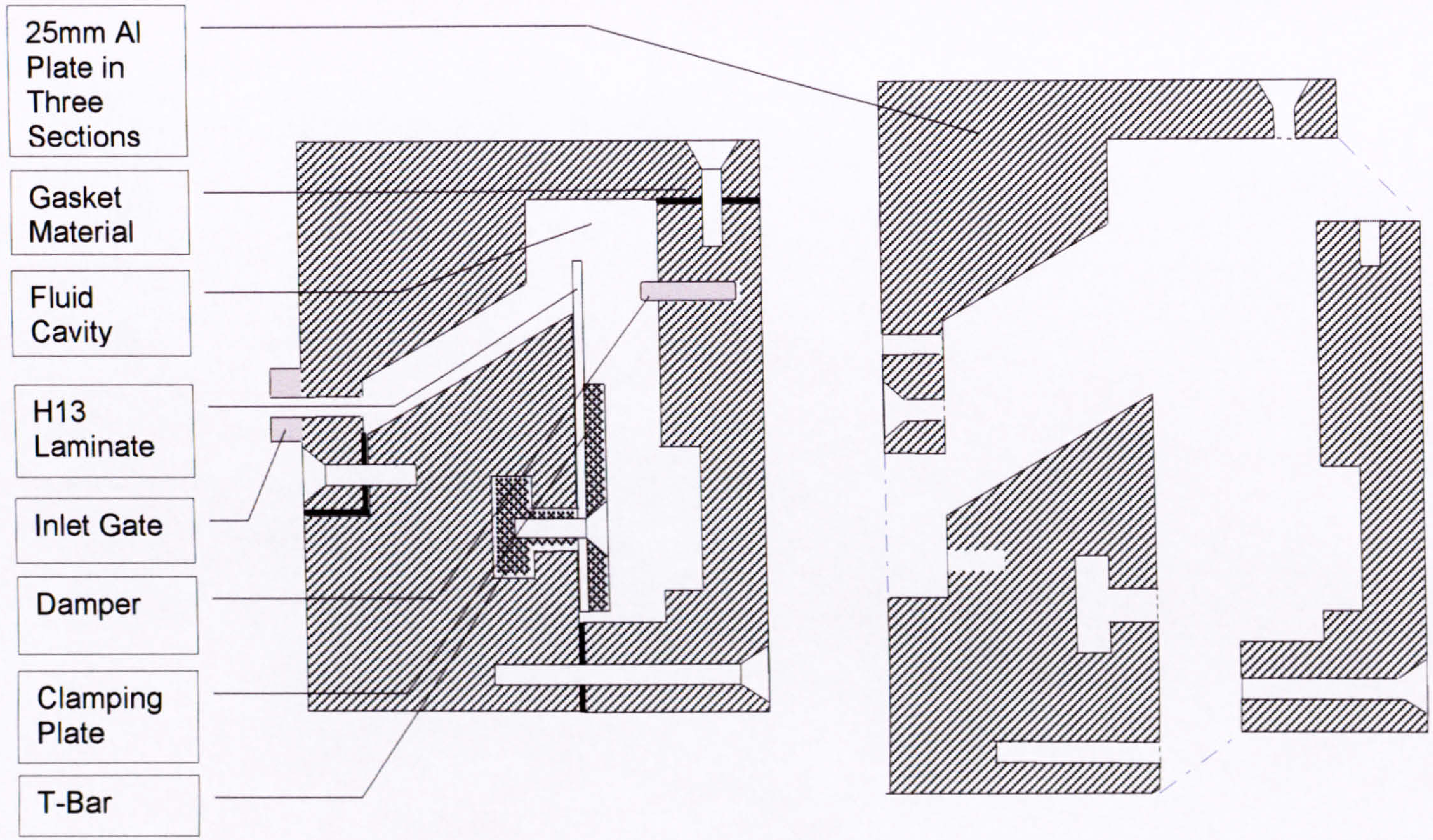
A deflection testing rig could be a suitable solution for deflection appraisal of individual laminates in a production pressure die-cast die. There were, however, limitations to the effectiveness of the mathematics used to scale down the problem of viewing deflection.

Conventional elastic displacement theory ($\O = {}^{M}/_{EI}$ [where $I = bh^3 / {}_{12}$]) was used in the formulation of a method to scale down the die-casting process so that it could be run on a bench top. As Szilard (1974) points out, these calculations are for strictly static loads, whereas the effects of fluidity, turbulence and flow in a die-cast die all act on the laminate in a dynamic way. Establishing the exact effect of a dynamic load on a laminate in a die is field of computational fluid dynamics and would make the process almost impossible to scale down accurately due to its complexity.

Addendum: The approach was later abandoned due to the difficulties listed above and it was decided that the only true way to identify deflection was to run an actual laminate test-die and establish some other means to measure deflection. This was to study the witness mark left on the castings.

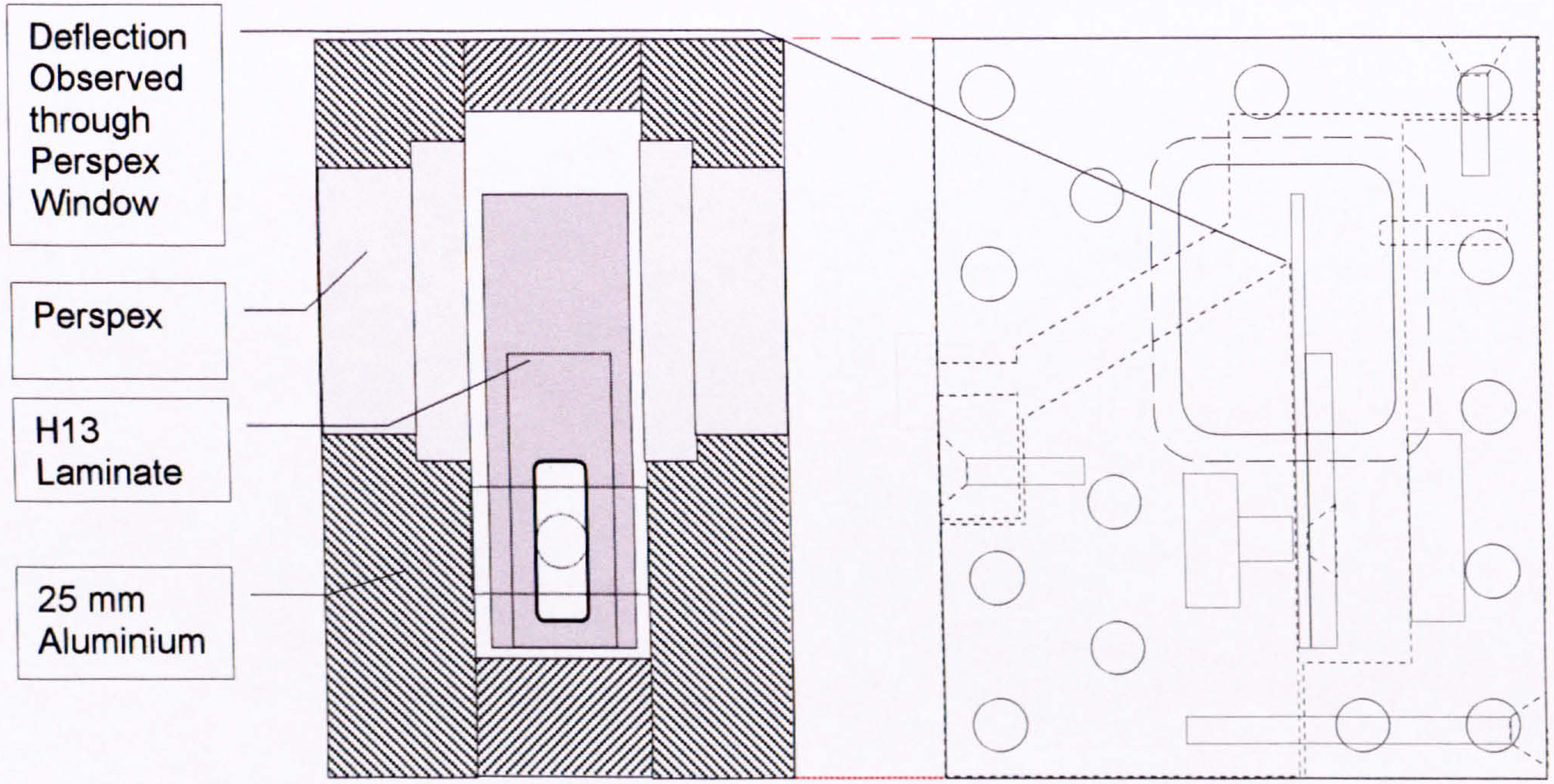
5. References

Szilard, R., (1974) **Theory and Analysis of Plates: Classical and Numerical Methods,** *publ. by Prentice Hall Inc.*, Englewood Cliffs, New Jersey, USA, ed. by Szilard R., ISBN 0-13-913426-3.



TITLE:	Schematic of Deflection Testing Apparatus with Exploded View (Side View)
DO NOT SCALE	
Dwg No:	One
Scale:	1:2
Date:	12-09-97
Material:	Die – H13 Set - N2
Finish:	N/A
Heat treatment:	Vacuum

NAME: Rupert Soar | Figure 1. Elements of deflection testing apparatus | Revision no:



TITLE:

Schematic of Deflection Testing Apparatus with Exploded View (Face View)

DO NOT SCALE

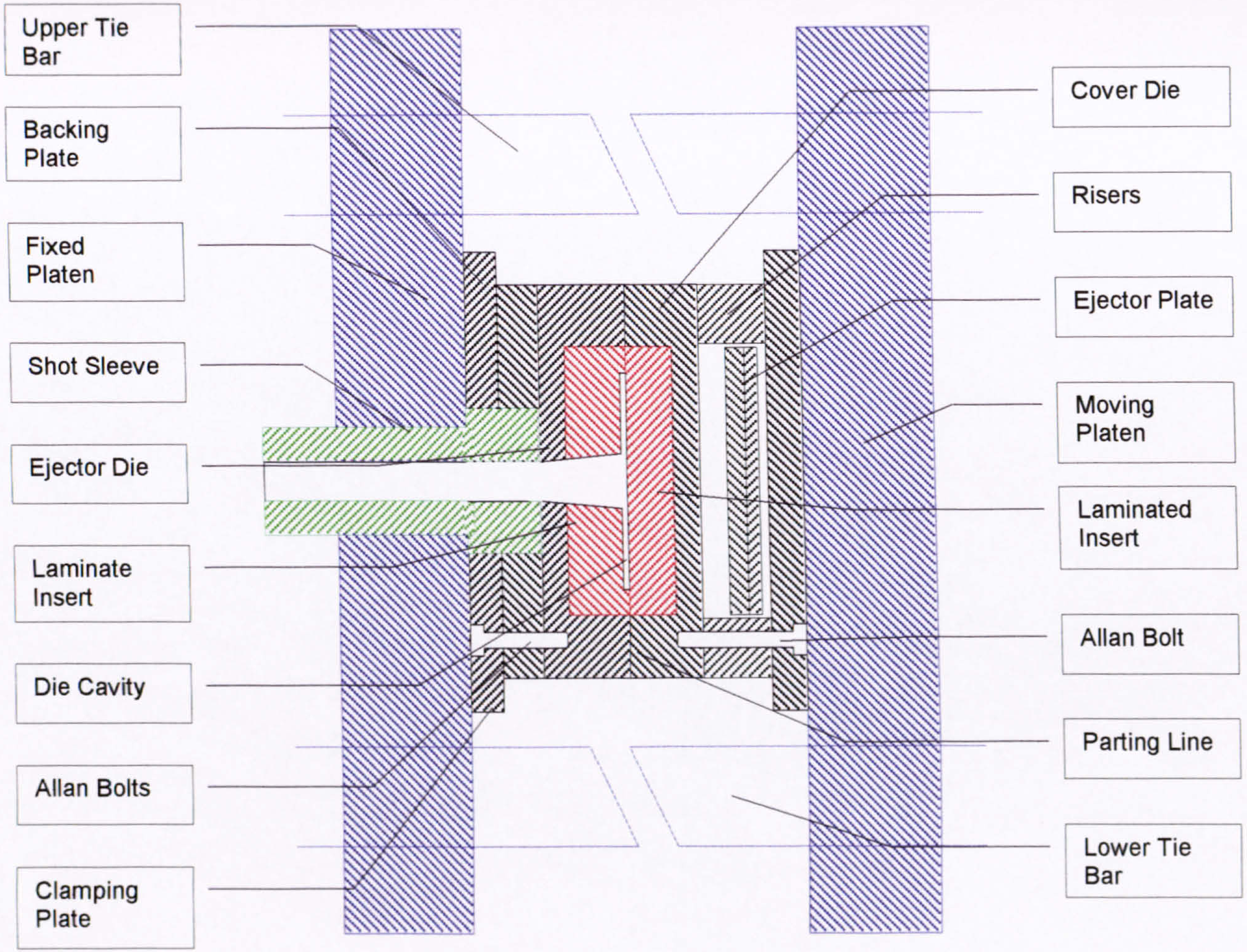
Dwg No:	Two
Scale:	1:2
Date:	12-09-97
Material:	Die – H13 Set - N2
Finish:	N/A
Heat treatment:	Vacuum

NAME: Rupert Soar

Figure 2. Cross section of deflection testing apparatus

Revision no:

Appendix V: Schematics for the Laminate Test-die Relating to Chapter Six and Chapter Eight.

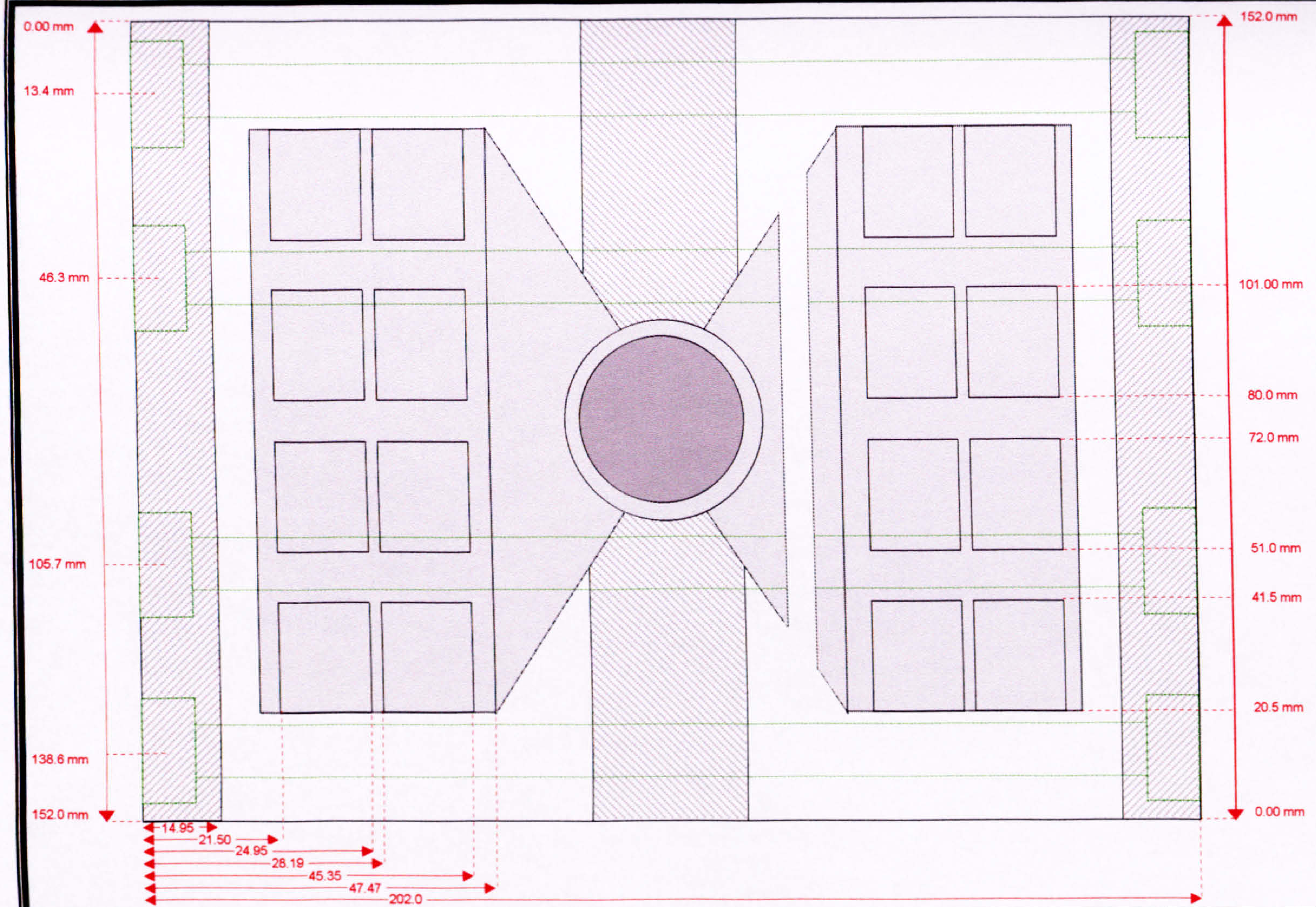


TITLE:	EMB 100 (10b) Side View of Die-set & Laminate Insert Showing Shot Sleeve.
DO NOT SCALE	
Dwg No:	Two
Scale:	1pt: 2mm
Date:	09-04-97
Material:	Die – H13 Set - N2
Finish:	N/A
Heat treatment:	N/A

NAME: Rupert Soar

Figure 1. Location of die-set in fixed and moving platens

Revision no:

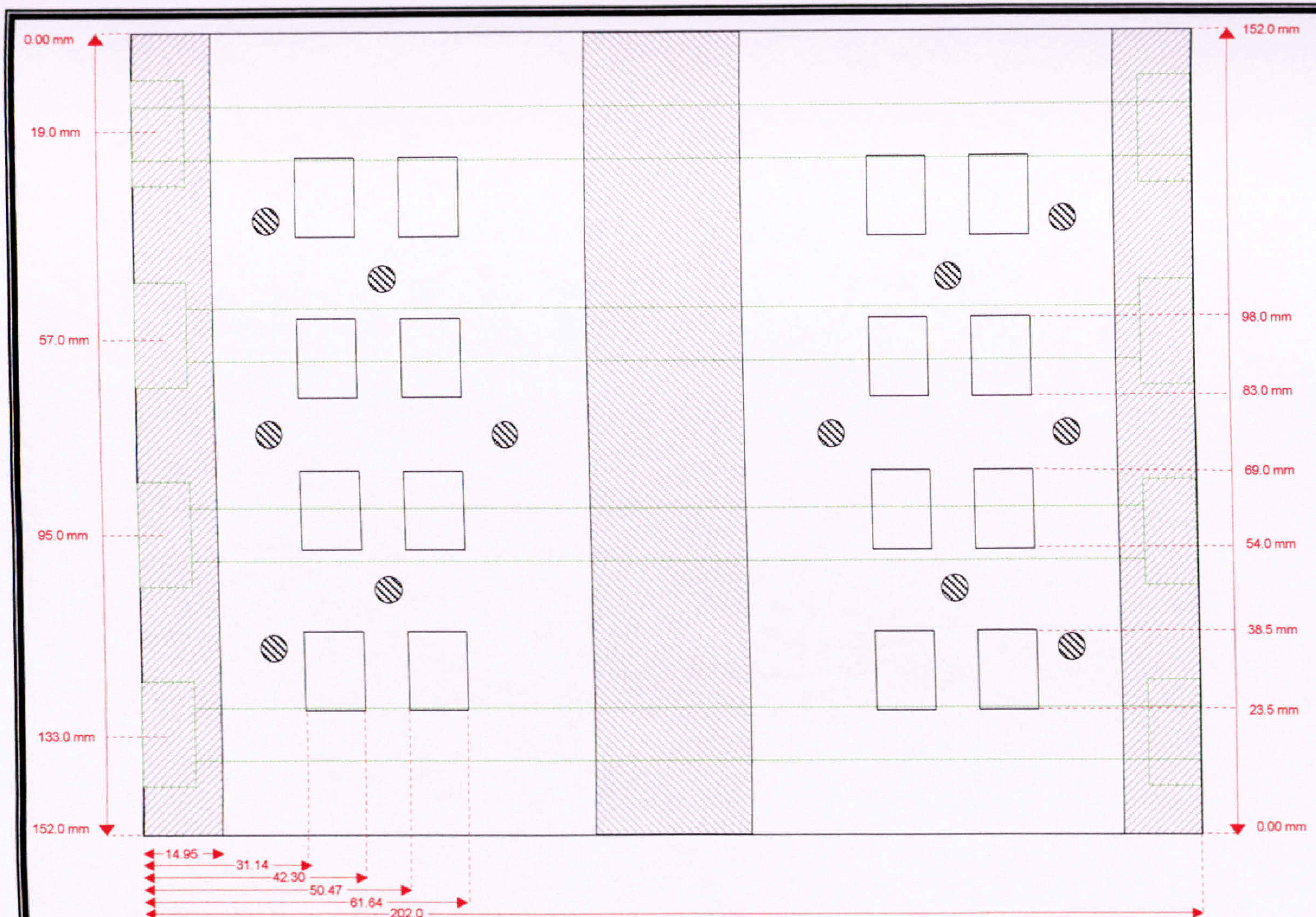


TITLE:	Laminate Test Die . Plan View of Cover Die.
DO NOT SCALE	
Dwg No:	Four
Scale:	1:1.2
Date:	25-07-97
Material:	1mm thick H13
Finish:	As Rolled
Heat treatment:	Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 2. Dimensions for laminate cover die insert

Revision no:



TITLE:

Laminate Test Die . Plan View of Ejector Die.

DO NOT SCALE

Dwg No: Six

Scale: 1:1.2

Date: 25-07-97

Material: 1mm thick H13

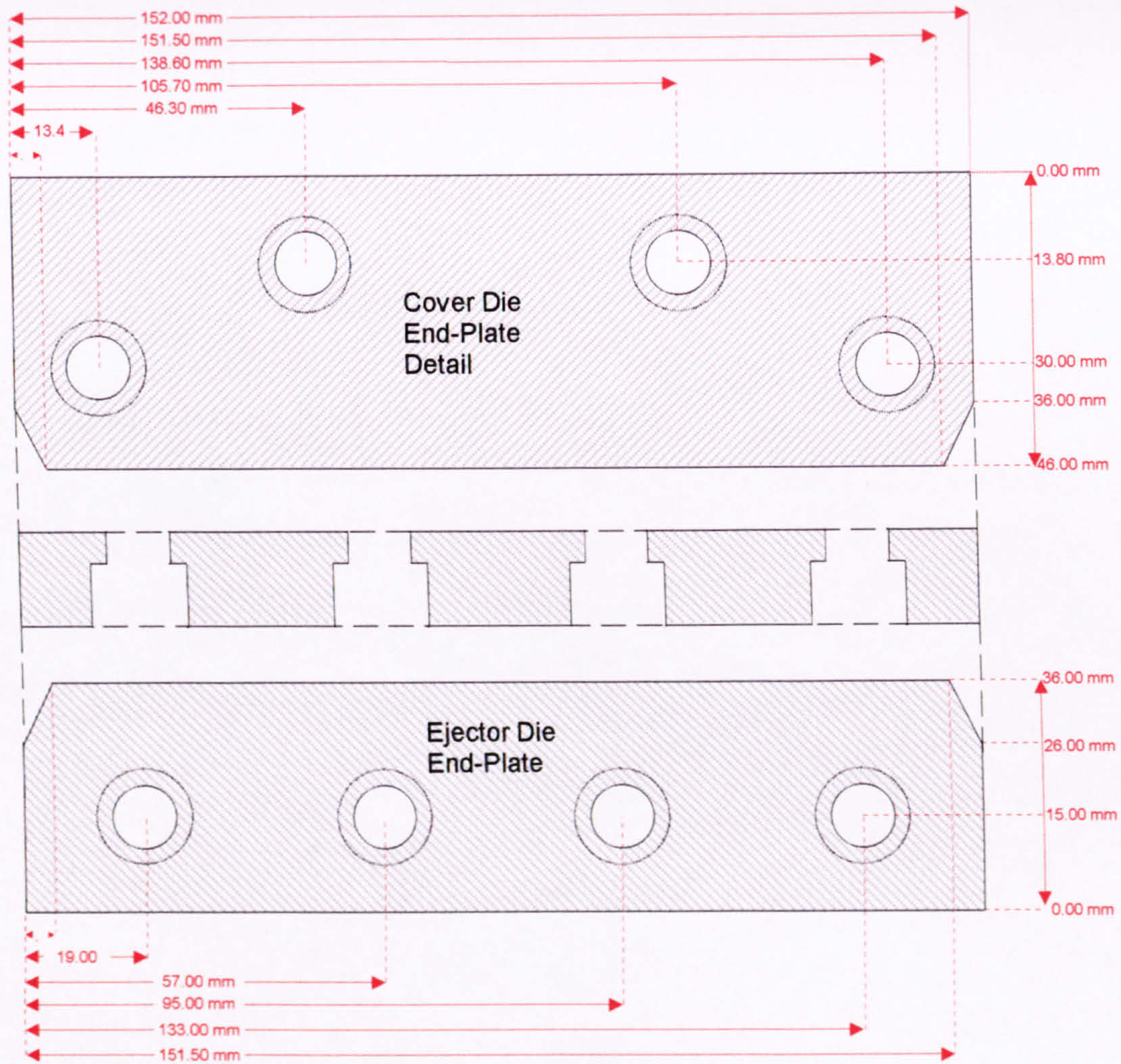
Finish: As Rolled

Heat treatment: Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 3 Dimensions of laminate ejector die insert

Revision no:

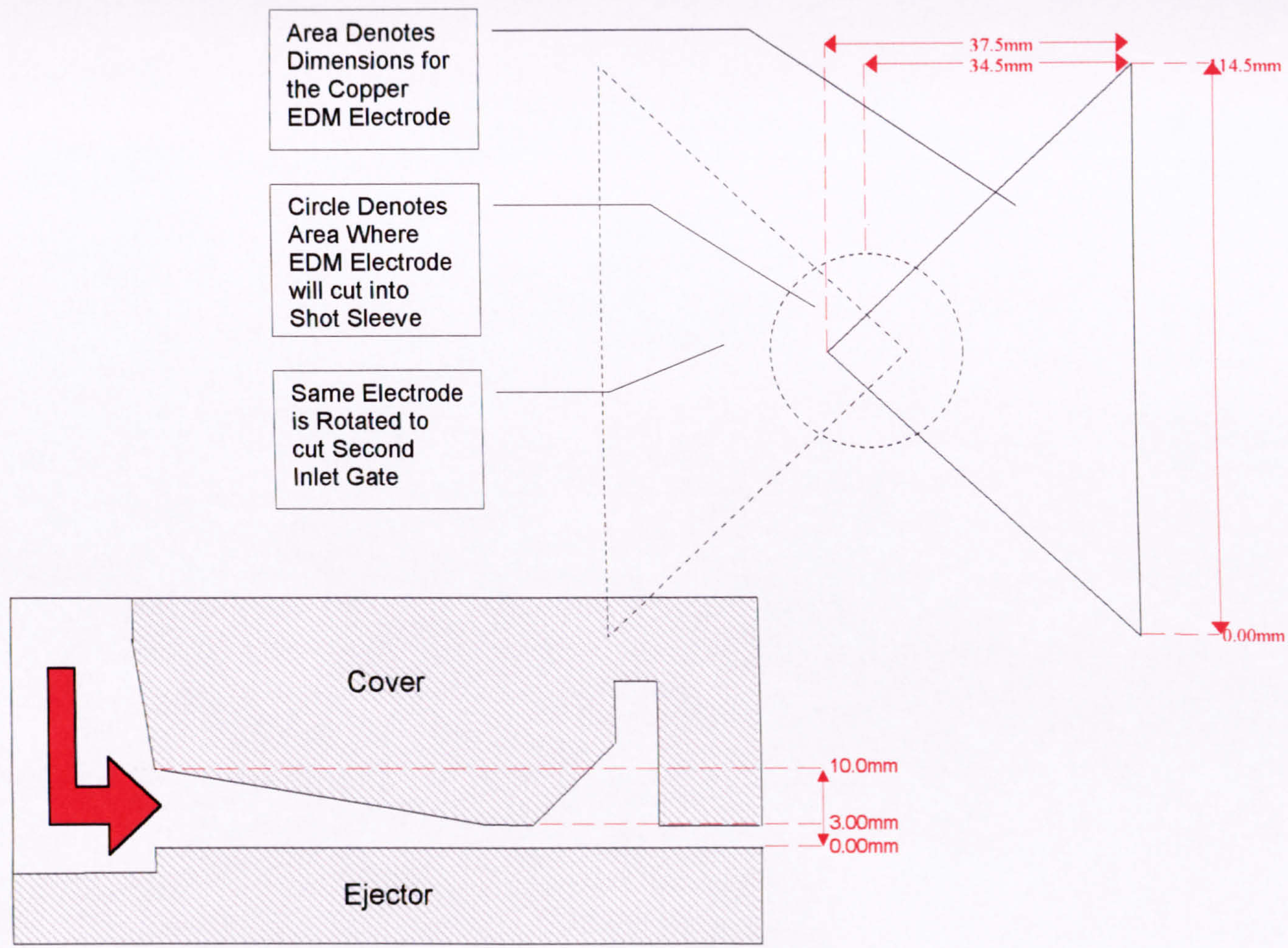


TITLE: Cross-section Detail of End-Plates, 2no at 14.95 mm Thick	
DO NOT SCALE	
Dwg No:	Eight
Scale:	1:1.2
Date:	25-07-97
Material:	Die – H13
Finish:	Fly cut
Heat treatment:	Vacuum 48-52 Rc

NAME: Rupert Soar

Figure 4 Detail of clamping plates for laminate inserts

Revision no:



TITLE: Plan & Cross Section of the Inlet Gate.

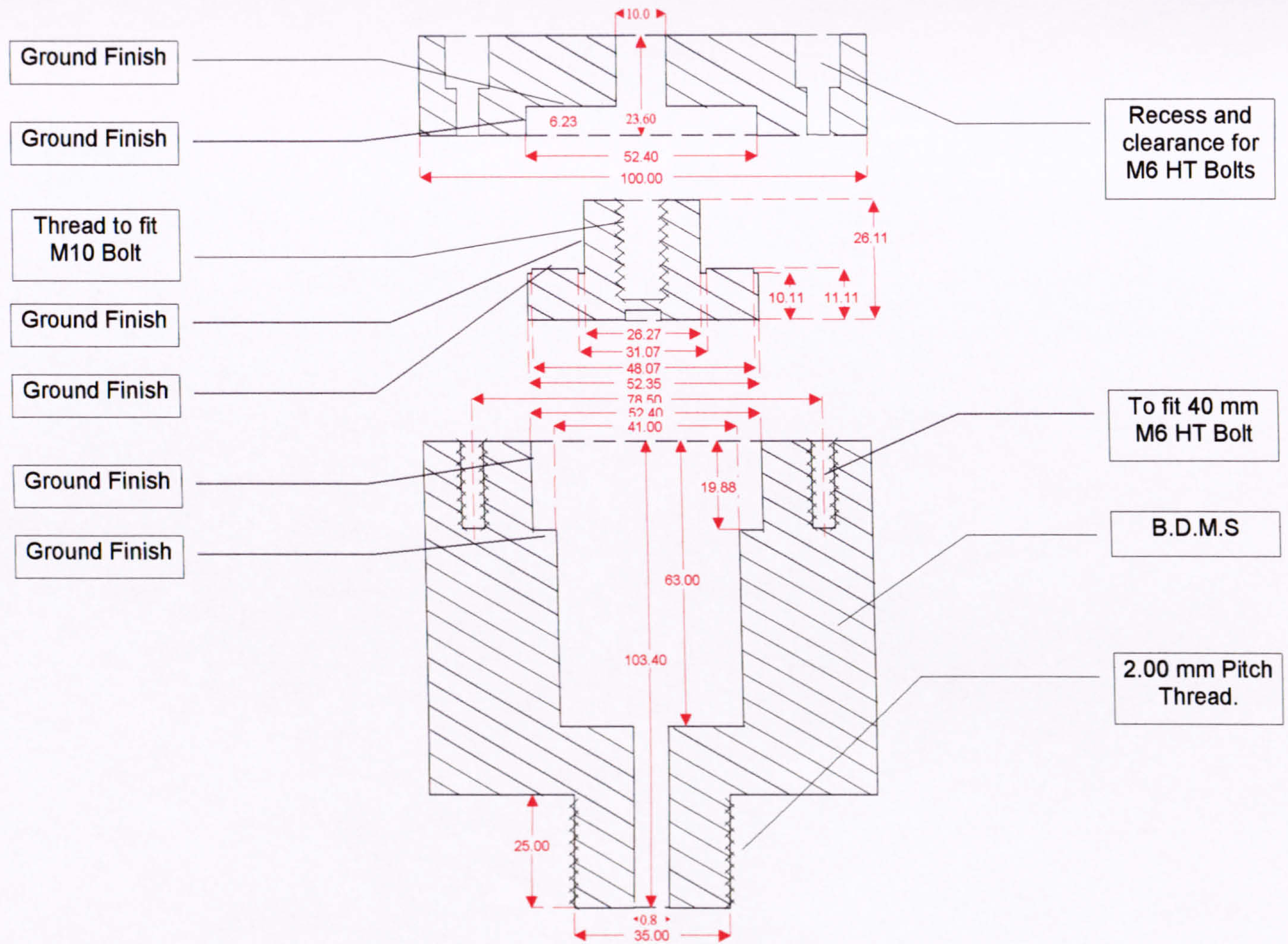
DO NOT SCALE

Dwg No:	Nine
Scale:	1:1
Date:	01-08-97
Material:	H13
Finish:	EDM 0.1 - 0.2 R_a
Heat treatment:	N/A

NAME: Rupert Soar

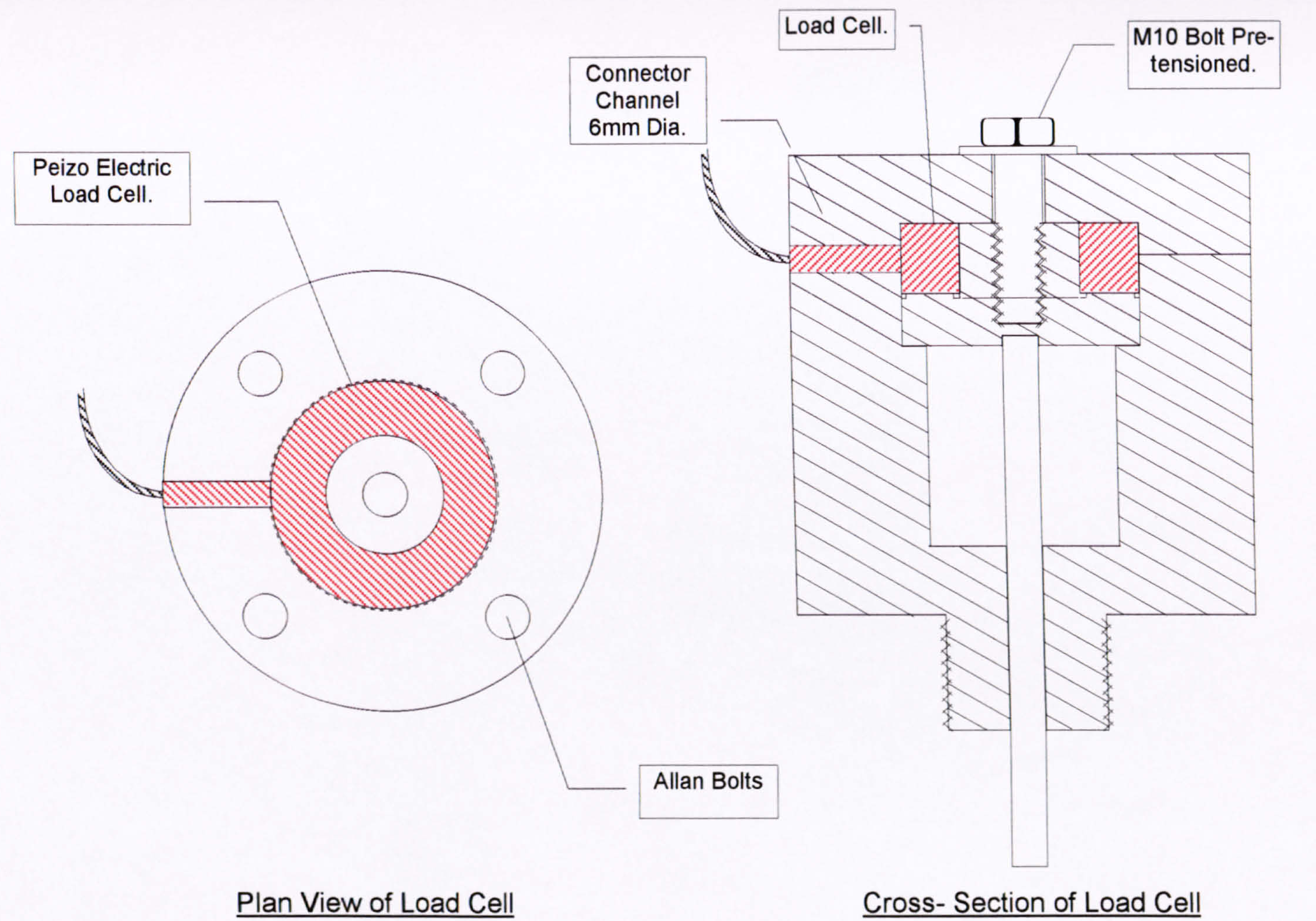
Figure 5 Plan and Cross-section of inlet gate

Revision no:



TITLE: Schematic of Elements of Peizo Load Cell Device for Insertion into the Rear of the Ejector Die	
DO NOT SCALE	
Dwg No:	Eleven
Scale:	1:1.5
Date:	12-09-97
Material:	B.D.M.S
Finish:	Ground
Heat treatment:	N/A

NAME: Rupert Soar | Figure 6 Exploded view of load cell elements | Revision no:

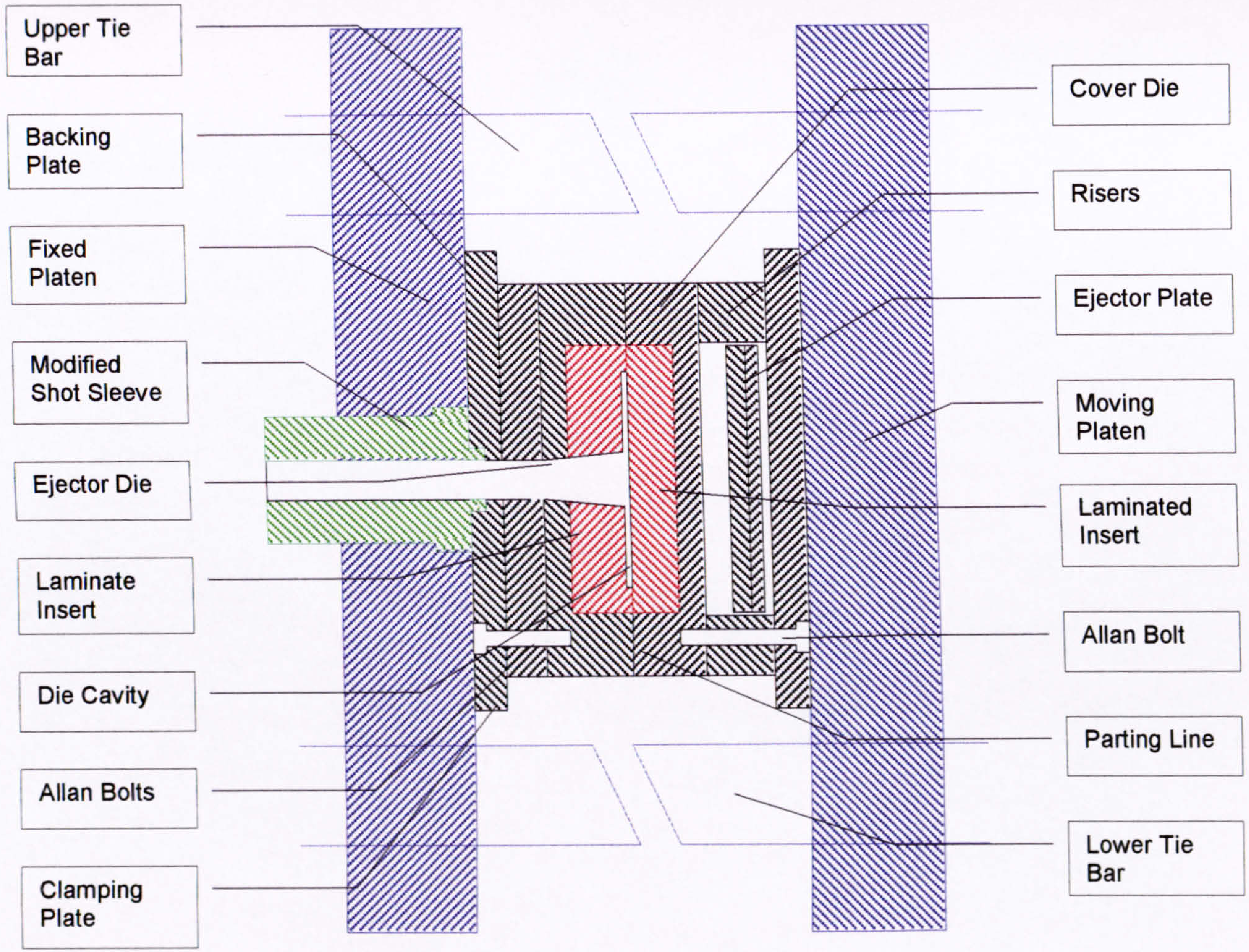


TITLE:	Schematic of Elements of Peizo Load Cell Device for Insertion into the Rear of the Ejector Die
DO NOT SCALE	
Dwg No:	Ten
Scale:	1:1.5
Date:	12-09-97
Material:	B.D.M.S
Finish:	Ground
Heat treatment:	N/A

NAME: Rupert Soar

Figure 7. Plan & cross-section of load cell and housing

Revision no:



TITLE:

Frech 125 DAK

Side View of Die-set & Laminate Insert Showing Shot Sleeve.

DO NOT SCALE

Dwg No: One

Scale: 1pt: 2mm

Date: 12-06-98

Material: Die – H13 Set - N2

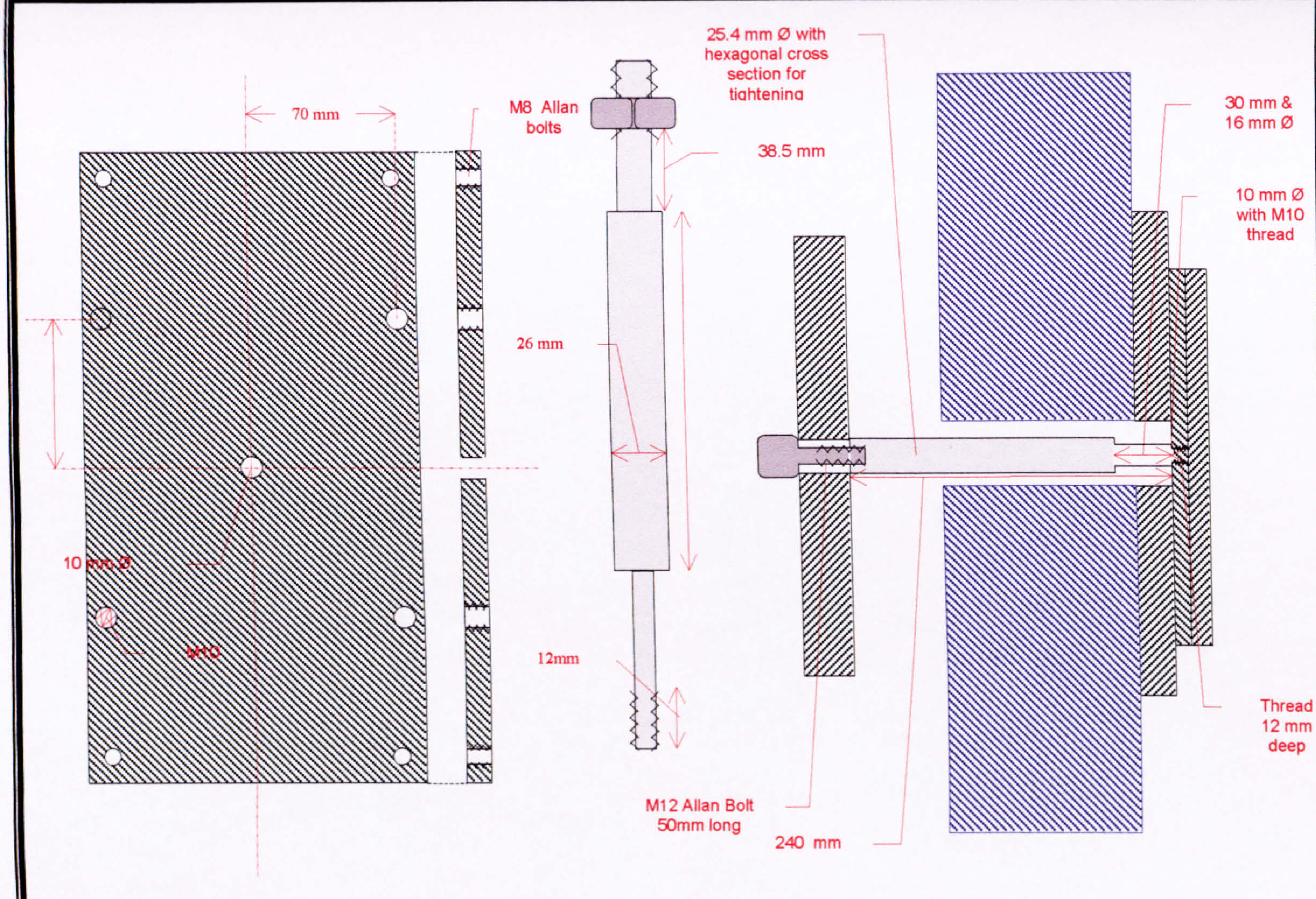
Finish: N/A

Heat treatment: NA

NAME: Rupert Soar

Figure 8. Modified injection unit for laminate test-die

Revision no:



TITLE: Schematic of Modifications to Ejector Assembly for Frech 125

DO NOT SCALE

Dwg No: Fourteen

Scale: 1:1

Date: 12-06-98

Material: 4340

Finish: NA

Heat treatment: NA

NAME: Rupert Soar

Figure 9. Modifications to ejector assembly

Revision no:

Appendix VI: Refereed Papers, Proceedings and Journals by the Author

1. Soar R.C. and Dickens P.M. (1996) **Finishing Laminate Tooling with Stereolithography E.D.M. Electrodes,** *5th European Conference on Rapid Prototyping and Manufacturing,* Finland, June 4th-6th 1999, pp87-106.

2. Soar R.C., Arthur A. and Dickens P.M. (1996) **Processing & Application of Rapid Prototyped Laminate Production Tooling,** *The Second National Conference on Developments in Rapid Prototyping and Tooling,* 18th-19th November 1996, at Buckingham College, UK, ed. by G.Bennett, pp 65-77.

3. Soar R.C. and Dickens P.M. (1996) **Design of Laminate Tooling for High Pressure Die-casting,** *The Symposium of the International Society for Optical Engineering (SPIE),* Rapid Product Development Technologies, 18-19th November 1996, Boston Massachusetts, USA, pp198-210

4. Soar R.C. and Dickens P.M. (1997) **Deflection and the Prevention of Ingress within Laminate Tooling for Pressure Die-Casting,** *Solid Freeform Fabrication Symposium 1997,* August 11-13 1997, The University of Texas at Austin, Texas, USA, pp307-317.

5. Bocking C., Jacobson D.M., Sangha S.P.S., Dickens P.M. and Soar R. (1997) **The Production of Large Rapid Prototype Tools Using Layer Manufacturing Technology,** *The GEC Journal of Technology (formerly the GEC Journal of Research),* Volume 14, Number 2, 1997, pp110-115.

6. Soar R.C. and Dickens P.M. (1998) **The Use of Laminate Tooling for the Production of Prototype Pressure Die-Cast Dies,** *Time Compression Technologies Conference 1998,* 13-14th October, Nottingham, UK, pp332-343.

7. Soar R.C. and Dickens P.M. (1998) **Rapid Prototyping Opportunities: Laminate Tooling for Aluminium Die-casting,** *The Aluminium '98 Conference,* 23rd-24th September, 1998, Messe Essen, Germany.

8. Soar R.C. and Dickens P.M. (1998) **Large Scale Prototypes & Tooling from CNC Laser Cut Sheets or 'Laminate Tooling',** *VIGIE Prototypage Rapide* - Bulletin Trimestriel de Veille et de Signalement, February/ March/ April 1998, Number 9, pp18-20

Finishing Laminate Tooling with Stereolithography E.D.M. Electrodes

Rupert C. Soar & Dr. P. M. Dickens

Presented at: 5th European Conference on Rapid Prototyping and Manufacturing, Finland, June 4th-6th 1996, pp87-106

ABSTRACT

A two-part experiment was conducted, firstly, to produce laminate tooling from laser cut steel sheets. Secondly, the study looked at the feasibility of removing the stepping that occurs within laminate tools using Electro-Discharge Machining (EDM).

The electrode needed for the EDM process was formed from the CAD model of the original part. A Stereolithography part was produced from the CAD model which was then electroplated with copper. A pilot study was run to see if the stepping in the laminate steel could be removed from a simple thermoforming tool. This was successful, and formed the basis for the main experiment which was to produce a two part injection moulding laminate tool. The same CAD files were again used to form the electrodes needed for the EDM process that had been used to form the two halves of the tool. This paper shows how that study proceeded and the results that were obtained.

INTRODUCTION

Rapid Prototyping is establishing itself as a means of enabling competitiveness and reducing time-to-market in businesses around the globe. In the last few years, there has been a shift of attention within this technology. Developers see greater potential in the creation of tooling, either directly or indirectly, from 3D-CAD data over the traditional modelling approach. It is this expansion of the technology which is now called Rapid Tooling in the UK. Techniques, such as Quickcast, Vacuum forming and thermal spraying, epitomise the indirect route for the production of tooling from CAD data, whereas greater interest is being shown in the various direct methods of producing a finished tool from CAD data. Such techniques include: -

- Laser sintering of metal powder followed by infiltration.
- Temperature resistant resins for stereolithography (SLA.)
- 3D printing with ceramics.

Within this field of direct tooling, another technology has not so much appeared but been re-discovered. During the late 1970's Professor Takeo Nakagawa *et al*[1] (1977) began to experiment with a concept that is now called Laminate Tooling. His concept was to produce blanking and deep drawing tools by profiling, stacking and then bonding individual laminates of sheet steel together.

The desired tool was first designed on a CAD station and sliced to the thickness of the steel sheet which would be used to make the tool. The data for each individual slice was then fed to a milling machine, electro-discharge machine (EDM) wire cutter or, later, a computer numerical controlled (CNC) laser. This would cut out the profile of that laminate and this process was repeated until all the laminates were produced. The laminates were then bonded together, either physically or mechanically, to form the complete tool.

For a blanking tool, the top sheet of the horizontally stacked laminates was thicker and made from bainitic steel, this formed the cutting edge for the tool. For a deep-drawing tool, the laminates were again stacked horizontally and the steps left by the process removed using an angle grinder. The resulting tools were considerably cheaper than conventionally machined tools, but their evolution was controlled by the development of laser technology and the slicing of Solid 3D-CAD data. The success of Nakagawa's work is evident in Hanai Engineering[2] (1995) in Japan which has produced around 10,000 production blanking and deep drawing tools.

In Europe, as well as the U.S.A., the use of laminate tooling has gone largely unnoticed. This is despite the work done by various groups around the world including Glozer & Brevick[3] (1992), Schreiber & Clyens[4] (1993), Vouzelaud & Bagchi[5] (1992), Walczyk & Hardt[6] (1994), to name but a few. In the past couple of years, however, there has been a change of attitude, industry's initial trepidation is on the turn. There are two reasons for this:

> Firstly, as the state of competitiveness increases around the world, so products must be targeted at more specific 'niche' markets. This requires tools which must give quality products but have a far shorter life cycle than ever before. To achieve this will require tooling for a range of industrial activities which perform more efficiently and for less cost.
> Secondly, industry did not take seriously the concept of stacking laminates to produce a tool, until stereolithography and its associated technologies. The success of taking sliced CAD data to produce a model or prototype has changed the way manufacturers view tooling production.

Established bureau's now realise the importance of support services to their prototyping and tooling businesses. In the U.K., Dundee University, Warwick University, Liverpool University and Nottingham University are all now exploring this technology. Interestingly, none of these groups are investigating blanking and deep drawing tools, and this can be said for all the research groups around the world. The emphasis has now moved to moulding techniques, including injection, blow, permanent and pressure die-casting. It is this technology and the possible ways of improving its utility for Rapid Tooling which will be discussed in this paper.

BENEFITS OF USING LAMINATE TOOLING FOR PROTOTYPE MOULDS

Modern mould design and development is a laborious task and is the reason why rapid tooling has evolved. Most tool-makers are familiar with EDM, either with wire or solid copper electrode. EDM is the most commonly used technique for producing accurate multi-piece moulds in materials such as tool steel. This process is time-consuming due to the sheer quantity of material which normally needs removing, and mistakes and alterations are expensive.

The alternative is to C.N.C. machine from solid stock. The machining process is fast but finishing is difficult. Deep vertical draws are a problem due to the milling head being obstructed on the descent, and sharp corners in the tool must often be finished by EDM. A laminate tool overcomes these problems as each layer is cut rapidly with a laser, which has great accuracy. Each profile can contain as complex a cross section as is required, forming a tool of limitless depth.

A further element with mould design is becoming more prevalent, that of temperature control within a working tool. As lead times shorten and production rates increase, so the demands on mould tools to be constantly at their working temperatures increases. At the beginning of any cycle, the tool must be at its optimum working temperature and, during a cycle, any excess heat generated must be removed. More importantly, the temperature over the entire working face must be controlled evenly.

At present, cooling and heating systems have been a matter of drilling straight bores through the back of the tool face. As the tool face rarely runs parallel to a drilled hole, so the efficiency of conventional cooling channels is limited and hot spots are a problem.

Manufacturers using gravity die casting rarely use heating or cooling mechanisms as they hold the cycle times down. This requires the operator to gauge the right temperature of the tool for the next shot. This attitude is changing through the need for shorter cycle times. With the tool running faster, heat must be dissipated efficiently to keep the tool within its operating parameters.

Research at MIT, under Sachs *et al*[7] (1995), suggests that conventional, straight, cooling channels cannot cool a tool face evenly. This can cause a build up of heat around corners and in those parts of the face which are too far away from the channels. They have shown that by laser sintering steel powder, they can create cooling channels, which conform to the face of the tool under which they pass.

This principle is equally applicable to laminate tooling. Complex conformal cooling channels can be modelled into a tool at the design stage, their efficiency can then be tested with FEM software. An example is shown Figure 1.

The benefits of using laminate tooling can be summarised as follows: -

- Conformal cooling channels with any cross section shape;
- Ease of disassembly for alteration;
- Easy replacement of damaged or worn elements;
- Exceptionally large tool design (the laser can cut profiles up to three metres by two metres);
- Direct production of the tool from a CAD model;

- Laminate tools can withstand thermal shock, as the propagation of cracks is arrested.

PROBLEMS ASSOCIATED WITH LAMINATE TOOLING

As with any new technology, laminate tooling has a number of inherent problems. These need to be addressed over the next few years and will include: -

- Adequate bonding of the laminates;
- Prevention of warp in the laminates;
- Prevention of delamination in the tool;
- Optimum design and depth of conformal cooling channels;
- Prevention of errors in CAD and DXF files prior to cutting;
- Laminate orientation.

Laminate tooling is unlikely to replace small, multi-piece tools in the existing market. This is due to the nature of mechanically binding the laminates that tends to be bulky. Small tools (<500×500×500 mm) will continue to be produced either from solid stock or from one of the new, direct, methods discussed previously. As production runs for tools shorten, so a faster return is expected from the tool used. Conventional methods of tool production are too expensive at these shorter runs as well as being restrictive in size. Because of this, manufacturers are becoming increasingly interested in the possibility of large (>500×500×500mm), short run (around 50,000 shots) tools.

THE DESIGN OF A METHODOLOGY TO ELIMINATE STEPPING

When designing a laminate tool, a key decision will be the thickness of the sheets that, once cut, will make up the tool. Many early attempts, both in the U.S.A. and Japan, looked at sheets of around 15-25mm thickness. At this time, the principle reason was that this thickness of steel was readily available and could be rolled accurately. This situation has changed. Closed loop control for both hot and cold rolling now allows for hard steels to be rolled accurately to one-millimetre, or below, in widths up to 1500mm. At this point in the design there is a trade-off. When laser cutting (or water jet cutting) the laser head operates only in X-Y co-ordinates (profiling lasers will give a bevelled cut, but at great cost and only over a limited angle and only through thin sheet). The resultant profile of the tool will be stepped. The thicker the laminate, the greater the step and therefore the higher the finishing operation. If the laminates are thinner then the closer the stepping will be to the desired shape and the less finishing will be needed.

It was work at Nottingham, under Dickens *et al*[11] (1996) to produce a large laminate tool for the production of foam inserts for car panels, which led to laminates of one millimetre and less.

To develop laminate tools to be used in injection, blow, die and permanent moulding, it was decided to use a hardened steel laminate, due to the heat and pressure present. A cold rolled hardened mild steel (E.N.42-E&F) was chosen with a high (0.7%) carbon content (C.S.70-80). The initial laser cutting operation would give a tool that could be used where fine detail would not be required. In order to produce the type of tooling required for this study, a rapid, secondary, finishing operation was needed. Various techniques have been adopted by groups around the world to produce the correct bevel on each laminate prior to bonding:

- CNC milling to form the bevel on each laminate (Stratoconception[8]);
- Using a profiling laser to produce the bevel on each laminate (MIT[7]).

All these techniques have struggled with indexing problems when putting the laminates together. Through the extensive work by Arthur, Cobb & Dickens[9] (1995) at Nottingham, we now have a process for coating copper directly onto SLA parts, which has been used as a finishing EDM electrode for production tooling. In a laminate tool, most of the material has already been removed through the laser cutting operation leaving only a finishing operation to remove the steps. An SLA electrode could then be used to remove the material which forms the step, in order to produce a finished tool.

A benefit of this technique is that the EDM machining operation is performed after the laser cut laminates have been assembled. This key difference means that if the laminate tool is slightly oversized, due to discrepancies in the DXF files or the laser cutting operation, this error will be removed by the EDM electrode. If accuracy is not critical, then electrode size can be increased if the tool is too large.

Therefore, the object of this work was to combine the techniques of producing laminate tools and EDM finishing with SL electrodes. To test this idea, two experimental tools were produced. The first was a vacuum forming tool which formed a pilot study for the main experiment.

THE PILOT STUDY

Figure 2, shows a laminate tool which was the result of an MSc project by Wilcox[10] (1994), at the Centre for Rapid Prototyping at Nottingham. The objectives of the project were:

- To investigate the ease by which a solid 3D-CAD model could be sliced into DXF files.
- Using these files to laser cut thin mild steel sheet.
- Assembling the sheets into a laminate tool.
- Vacuum forming parts from the finished tool.

The part to be formed was a food container with dimensions of 100×100×65mm. This had a steep draft angle with complex fluting which would clearly show if the resultant steps in the tool were too coarse to produce an accurate part. The base was flat so that the finish on the assembled laminates could be assessed for accuracy in the laser cutting process. The stepping effect at the end faces of the tool can also be seen in Figure 2. During subsequent vacuum forming, much of this stepping detail was not transferred to the polystyrene sheet that was formed into it. For the pilot study this tool was used to establish whether the stepping could be completely using the SLA electrodes.

The objective of the pilot study was, to produce an SLA model of the food container. The model was used to form an EDM electrode as in Figure 3. This electrode was then used to spark off the laminates from the original vacuum forming tool. The original model of the container was shrunk by an offset of 0.2 mm to account for the thickness of the copper deposited. The model was then built in solid acrylic on the SLA 250 machine with a 10mm blind hole placed in the top side to hold a steel peg. This peg would hold the electrode to the EDM machine.

No finishing was done to the SLA model to see if the electroplating process would fill in the fine stepping that occurs in stereolithography. A three-millimetre hole was drilled through the base of the SLA model. This would allow dielectric fluid to be flushed into the centre of the sparking face. The steel peg was produced and this also had a three-millimetre hole through its centre. Dielectric fluid could pass through the centre of the peg and down through the SLA part. Following this, the part was then coated with silver paint and electroplated with copper to a thickness of 0.2 mm. The electrode can be seen in Figure 4.

Parameters were set on the EDM machine to prevent any excessive heat build up in the electrode which could cause premature failure of the coating. During the sparking process, material removal rate was recorded and plotted. This was to see if any indication could be given as to the time required to spark, so that only the steps were removed and no more.

The EDM operation was run for 24 hours, during which the electrode descended into the tool only in the z-axis. At this point, the electrode had reached the bottom of the tool. On inspection, not all the stepping from the sides of the tool had been removed. The original tool had been slightly elongated as the steel sheet used to form the tool was fractionally thicker than the individual slices on the original CAD model. This elongation meant that the tools actual shape was an ellipse, and, as the electrode was round, a gap was left which was not sparked in this first operation. This gap contained much of the stepping detail that needed to be removed.

To remove the steps in the gap, the EDM machine has an orbiting function that allows an offset in the x and y-axis to be defined. The electrode was lowered back to the bottom of the tool and an orbiting offset of 0.2mm was set. This would remove the rest of the stepping and this continued for another 12 hours to finish the tool. The finished tool is shown in Figure 5.

The results of the data produced were plotted and are shown in Table 1. The graph shows that over 90% of the stepping was removed in the first four hours of sparking. Twenty hours were then spent sparking off the flat base of the tool. The finish was as good as any normally sparked tool, but by the end of the orbiting operation the electrode was beginning to break down.

BUILDING THE INJECTION MOULD TOOL

From the results of the pilot study, a second, two part injection moulding tool was proposed. The tool would test whether a laminate tool could form a suitable substitute for a conventional solid injection mould tool. The injection moulding model is shown in Figure 6.

The injection moulded part was small enough to use in our injection moulding machine. It also had steep, vertical, a narrow section which would readily show any defect in the tool material or construction (through overheating, material breakdown, poor finish etc.). The narrow, raised, elliptical section which ran along the centre of the tool would show any problems with de-lamination, which would appear as an ingress of plastic between the laminates.

Based on the findings of the pilot study, a methodology was produced to show the stages needed to form a finished laminate tool, this is shown in Table 2.

Stage I

To build a tool which could produce the test piece would require a two-piece mould. Polymer would be injected through the parting line, and any excess would be vented through the female tool, in addition, ejector pins were placed in the male tool. A model of the part was constructed in E.D.S. Unigraphics, and a DXF slicing sub-routine was developed. This would reduce the task of taking each slice into the separate DXF file necessary for the CNC laser operation.

To produce the moulds, the model was used as a subtraction function to form the negative shape in a solid block representing one half of the tool. As mentioned above a hard, cold rolled, steel with a high carbon content (C.S.80) was chosen with a thickness of 0.5mm because of the detail required to produce the thin elliptical up-stand in the part, as in Figure 7.

Stage II

Steel suppliers have wide tolerances when they roll steel. In this case the steel arrived with an extra 0.02mm over the specified 0.5mm thickness. This would add 0.02mm to every laminate in the tool and had to be compensated for in the CAD model. The model was re-sliced into DXF files with a pre-defined thickness for each laminate of 0.52mm.

Stage III

Conformal cooling channels were then defined in the tool. The channels formed a taurus around injection cavity and were set five millimetres from the mould face, these can be seen in Figure 8.

Four, ten-millimetre bolt holes were defined through both tools, and also four, five-millimetre holes which would eventually be used to bolt the laminates together. As an experiment, locating pins were defined in the model, these took the form of up-stands in the male tool and recesses in the female tool. The DXF files were then created for each laminate. Each file defined a laminate of 0.52mm (to allow for the oversized steel sheet).

Stage IV

Taking the original model of the part, the inside and outside surfaces were separated to form the two faces which would produce the electrodes necessary to spark the two halves of the tool. Both models were shrunk, using an offset of 0.2mm which would account for the thickness of the copper on the electrode. As with the pilot study, blind holes were created for the locating pins to hold the electrode to the EDM machine. S.T.L. files were created for both models, and these were then produced in acrylic on the SLA 250 machine as shown in Figure 9.

Stage V

Hollow steel rods were then attached to each acrylic model so that the finished electrode could be attached to the EDM machine. They were then coated in silver paint and electroplated with copper to a thickness of 0.2mm, as shown in Figure 10.

Stage VI

A metal jig was constructed with a sound base and vertical, threaded steel rods. The rods related to the bolt holes defined in each laminate. As each laminate was cleaned, it was positioned on the jig in order. Before cleaning the laminates, any burrs had to be removed by hand. This was straightforward and took four hours to complete. The laminates were then submerged in an ultrasonic bath to remove any grit or grease which would add to the thickness of the tool once assembled. Figure 11, shows one half of the tool prior to clamping.

Stage VII

The shut-off faces for each tool were used as jigs. Threaded rods were put in the shut-off faces, allowing the laminates to be stacked prior to bolting. The second shut-off face was then placed on top of the laminates and nuts applied to the protruding bolts. As the bolts were tightened the tool was continually checked for alignment and squareness.

The two faces that formed the parting line were not flat, this was due to inaccuracies that are present in the laser cutting operation. To ensure that the two halves of the tool met perfectly, both halves of the tool were EDM eroded together. This process took off any high spots in the parting face and helped in 'settling in' any errors in the locating pins. The eroded parting faces are shown in Figure 12. For the final part to this stage the inlet port and vent were bored using an EDM electrode.

Stage VIII

One half of the tool was bolted to the bed of the EDM machine and its matching electrode fixed to the machine's actuator. As no orbiting would be used for this operation, it was essential to position the electrode accurately. Coolant was flushed through the centre of the electrode through drilled holes, as in the pilot study and the machine parameters (z-limits) were set.

Stage IX

The erosion process was run and the graph plotted, as before. At the time of publication of this paper the sparking process had not been completed. The finished results will be shown in the paper given at the conference.

DISCUSSION

The sparking operation was a success, but the electrode did break down when sparking the male half of the tool. In addition, some steps were not completely removed at the point where the ellipse narrows off, due to too thin a coating of copper in the electrode. The female electrode was essentially concave, with tight, narrow details and sharp corners. All these elements create difficulties when plating an electrode, as the copper cannot deposit evenly over the entire surface. The male electrode presented no difficulties as plating was external and a smooth, even deposit of copper was achieved to 0.2mm. The male electrode was the most important of the two as this would impart the smooth finish to the surface which would be seen.

On this first injection mould tool there were no secondary techniques used to bond the laminates together. A second identical tool is under construction which will be bonded using a two-part epoxy resin applied to each laminate before clamping. In the pilot study, some of the laminates had bent away from their neighbours by around 0.1of a millimetre.

At this stage, we believe that as the steel is rolled, residual stresses are set up in the sheet. On the end laminates, the electrode has eroded the laminates at a very steep angle where material was removed. By removing the material from one side of a laminate the stresses still present in the other side may force the laminates to bend into the tool. Another cause may have been the localised heat which was generated at the sparking point. This heat may have distorted the laminates slightly, causing them to bend.

In the injection mould tool, the stresses in the rolled steel would be greater than the thicker steel used in the pilot study. To compensate for this, the steel was tempered in an attempt to see if these stresses could be reduced and so reduce any de-lamination. Because of this, the injection tool described here was not bonded, so that any de-lamination which may occur would be spotted easily. Initial sparking on the tool showed some delamination, but it hoped that suitable bonding will overcome this. We also wished to see if we could still produce injected parts, even if delamination had occurred. If the de-lamination were too great, then polymer would be forced between the laminates making the tool useless.

There was no opportunity to test the effectiveness of the conformal cooling channels at this stage, as they were not required to cool the tool. We are presently experimenting with channels which are not simply round. A star shaped hole in each laminate would result in a channel with a significantly larger surface area than a cylindrical shape. All these points are now being addressed, and further work is under way to see if we can develop tools for gravity die casting and, ultimately, pressure die casting. The results of this work will make up the next paper.

CONCLUSIONS

Previous work at the Centre for Rapid Prototyping, was undertaken to establish whether mild, rolled sheet steel at one millimetre thick could be laser cut into individual laminates. When these laminates were put together, the researchers hoped to produce a food container, which had previously been modelled in 3D-CAD, using vacuum forming. This paper outlines a pilot study carried out to establish whether the same CAD model of the container could be used to form a copper plated, SLA-EDM electrode. This electrode was subsequently used to remove the stepping in the same laminate tool.

Based on the success of this study, a nine stage methodology was developed. Firstly, to produce a working laminate injection mould tool, and secondly to remove the stepping using an SLA-EDM electrode built from the same solid model. Once the tool was finished, it was tested by running it on an injection moulding machine. For this second tool a sheet thickness of 0.5mm was chosen in tempered, high carbon steel due to fine detail and harsher operating environment in which the tool would be working.

Stepping was successfully removed, but problems occurred in the copper coating of the female electrode due to its complex, concave, shape which resulted in an uneven thickness of copper. This meant that on the unseen side of the injected polymer parts, some stepping was still visible.

Work is now commencing to improve laminate bonding and maximise conformal cooling channel efficiency in order to produce die cast and pressure die cast laminate tools.

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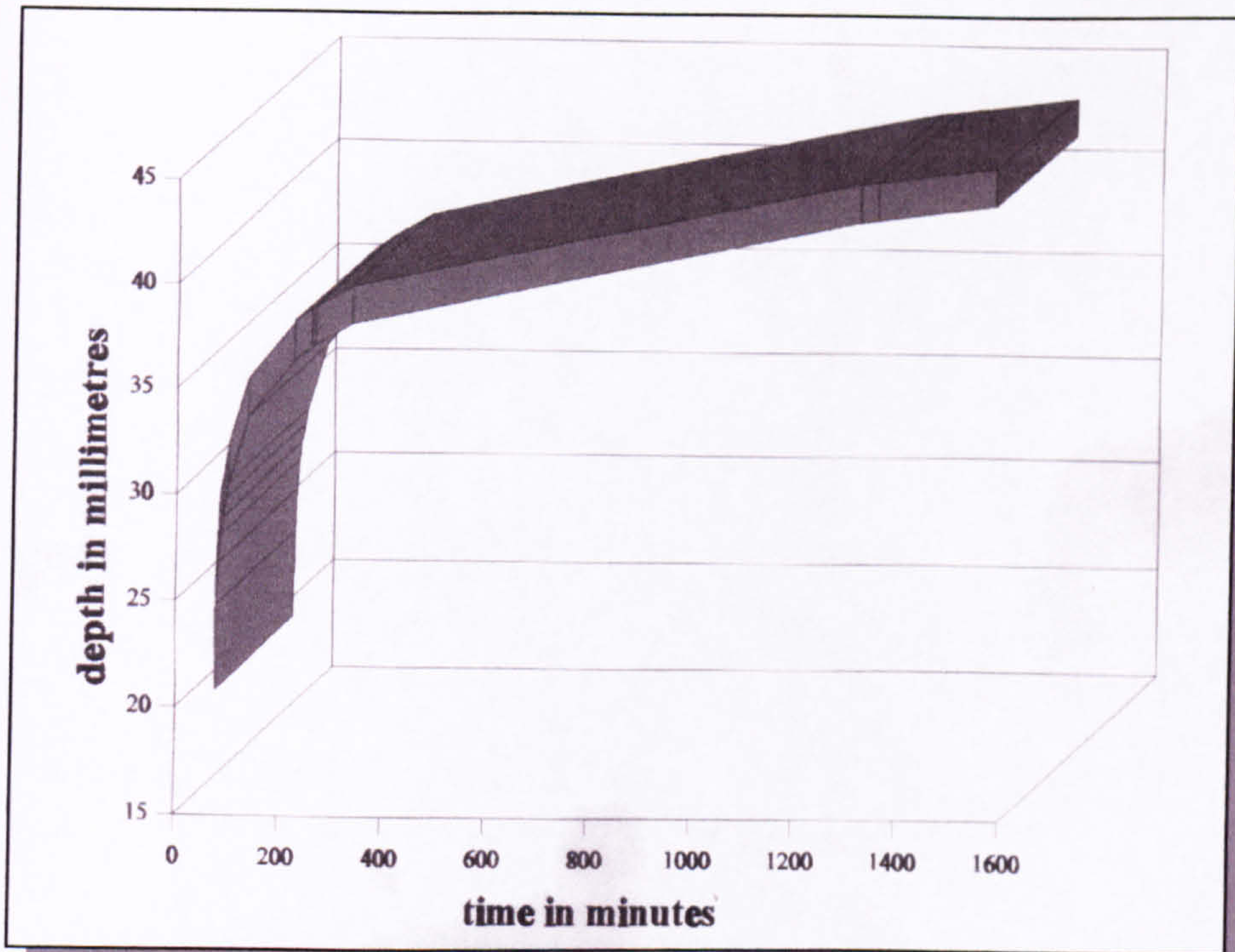

Table 1: Plotted results from the sparking operation.

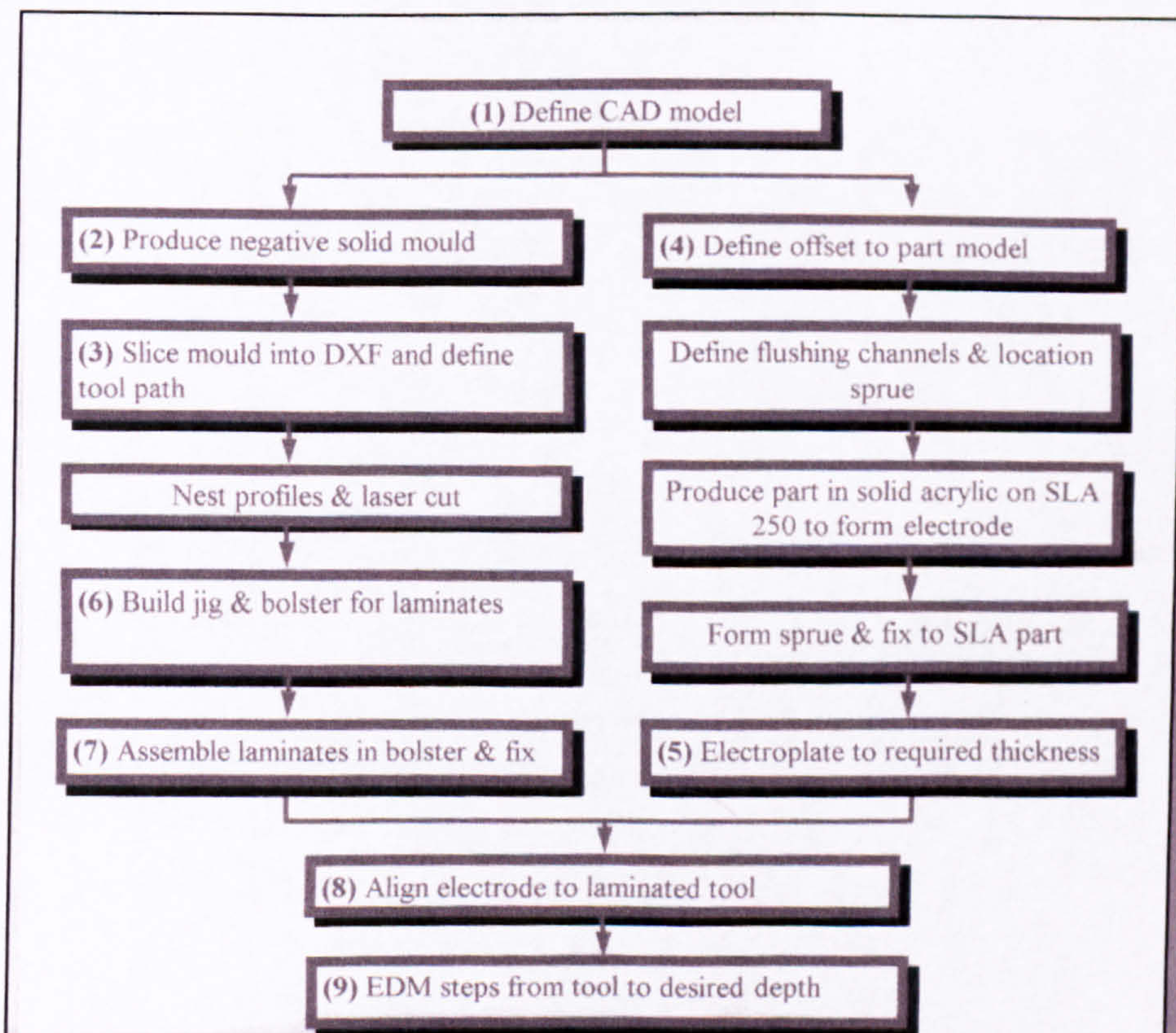

Table 2: Design methodology for a spark eroded laminate tool.

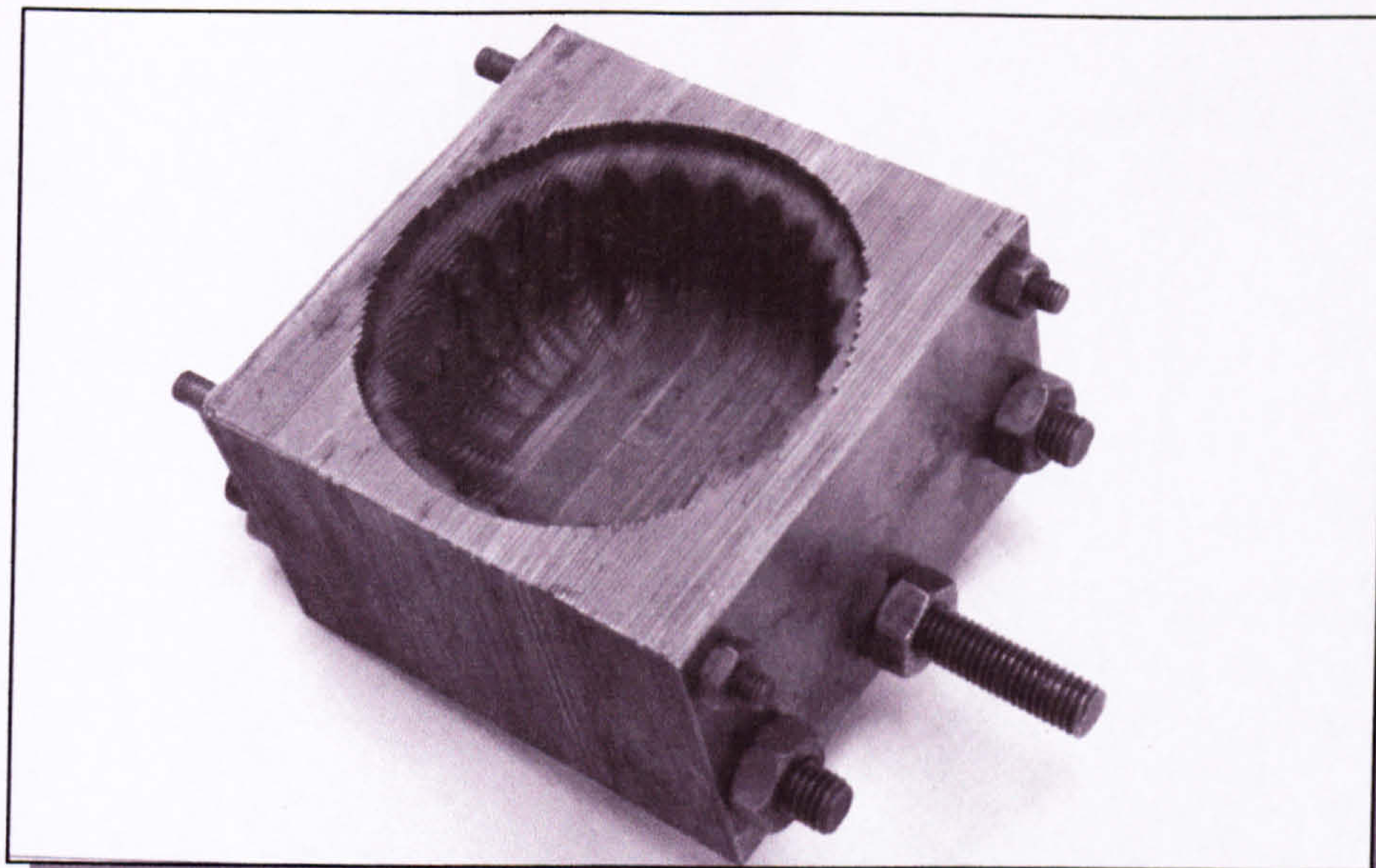

Figure 2: The laminate vacuum forming tool.

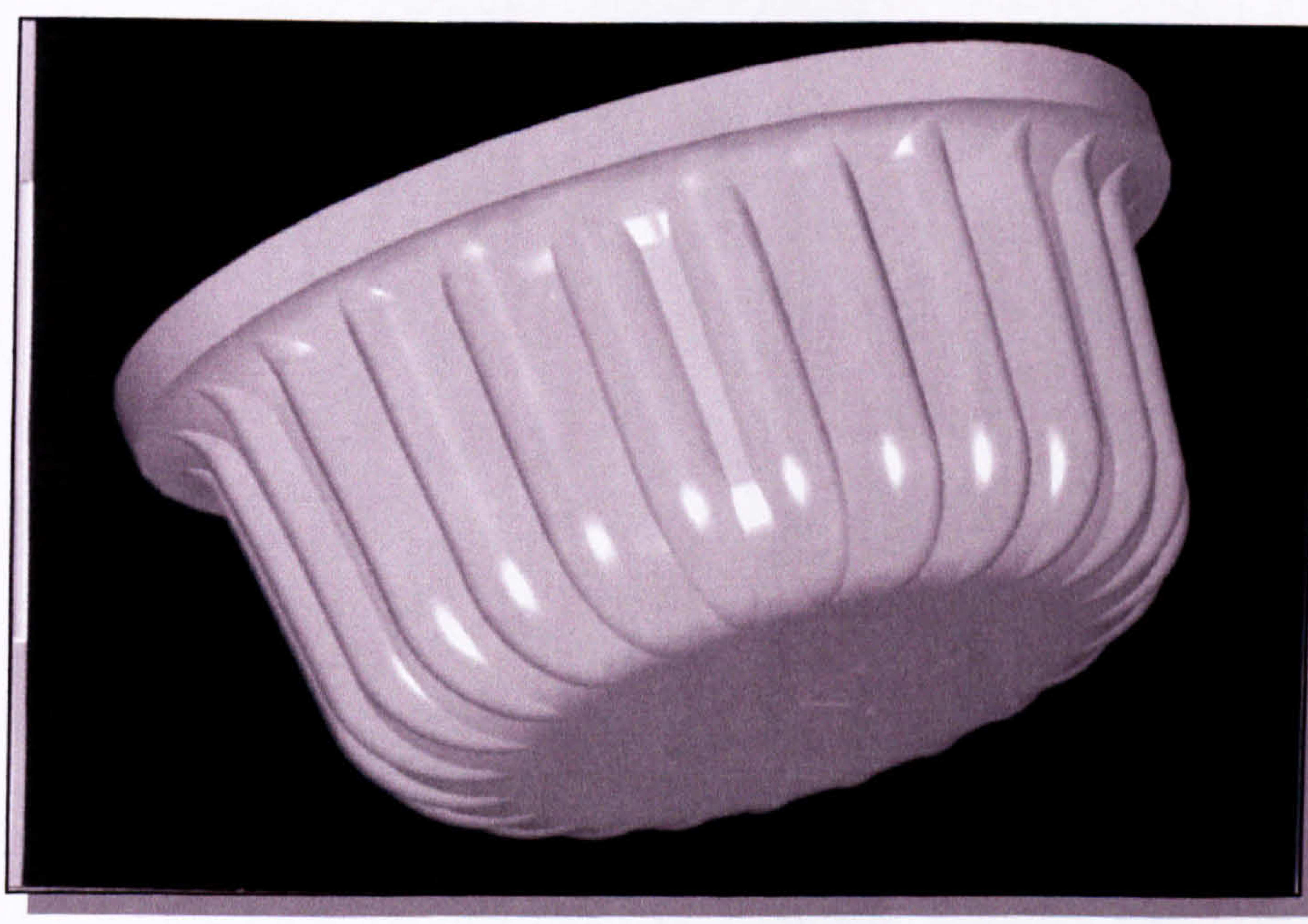

Figure 3: The initial CAD model used to form the tool.

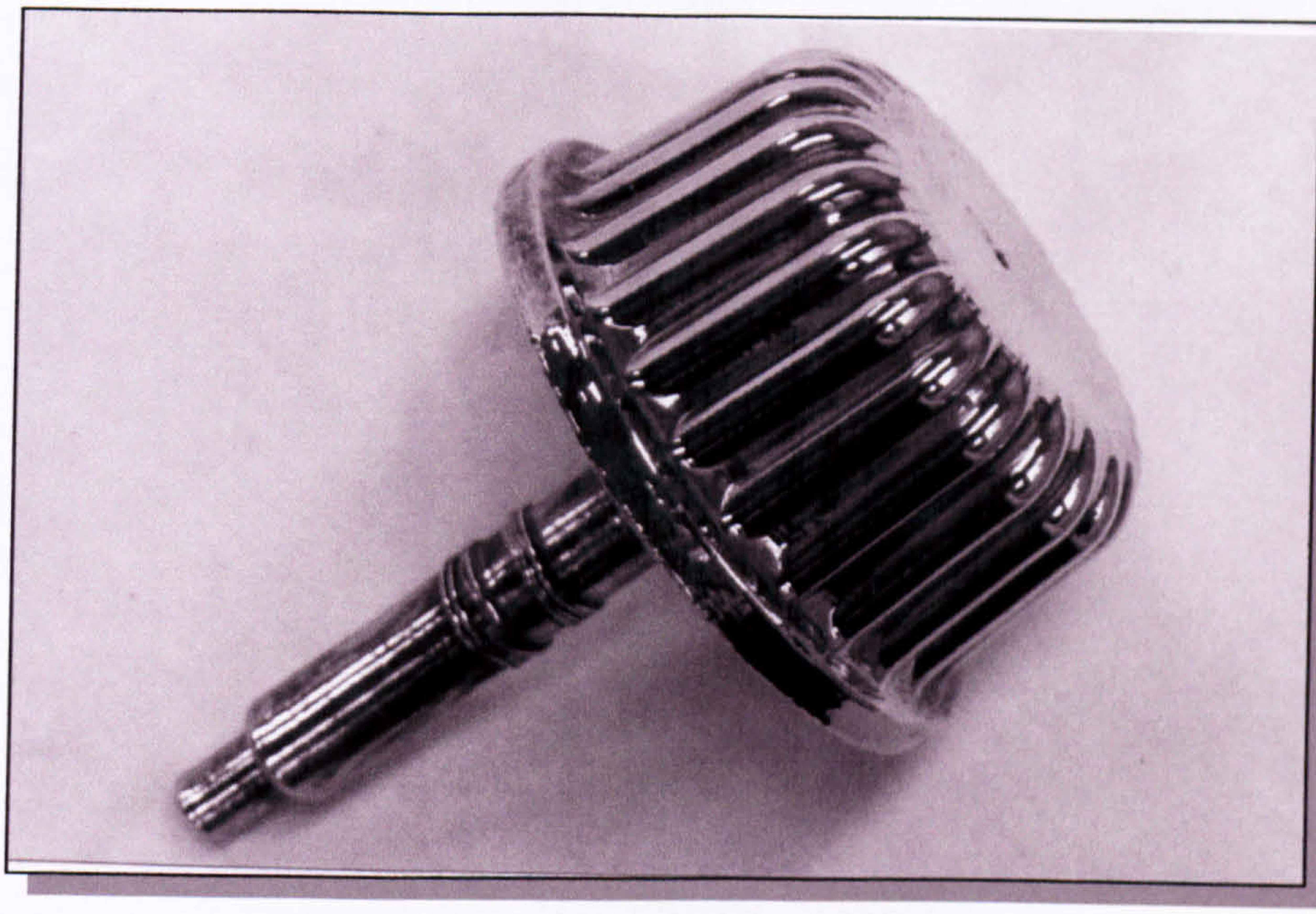

Figure 4: The finished EDM electrode.

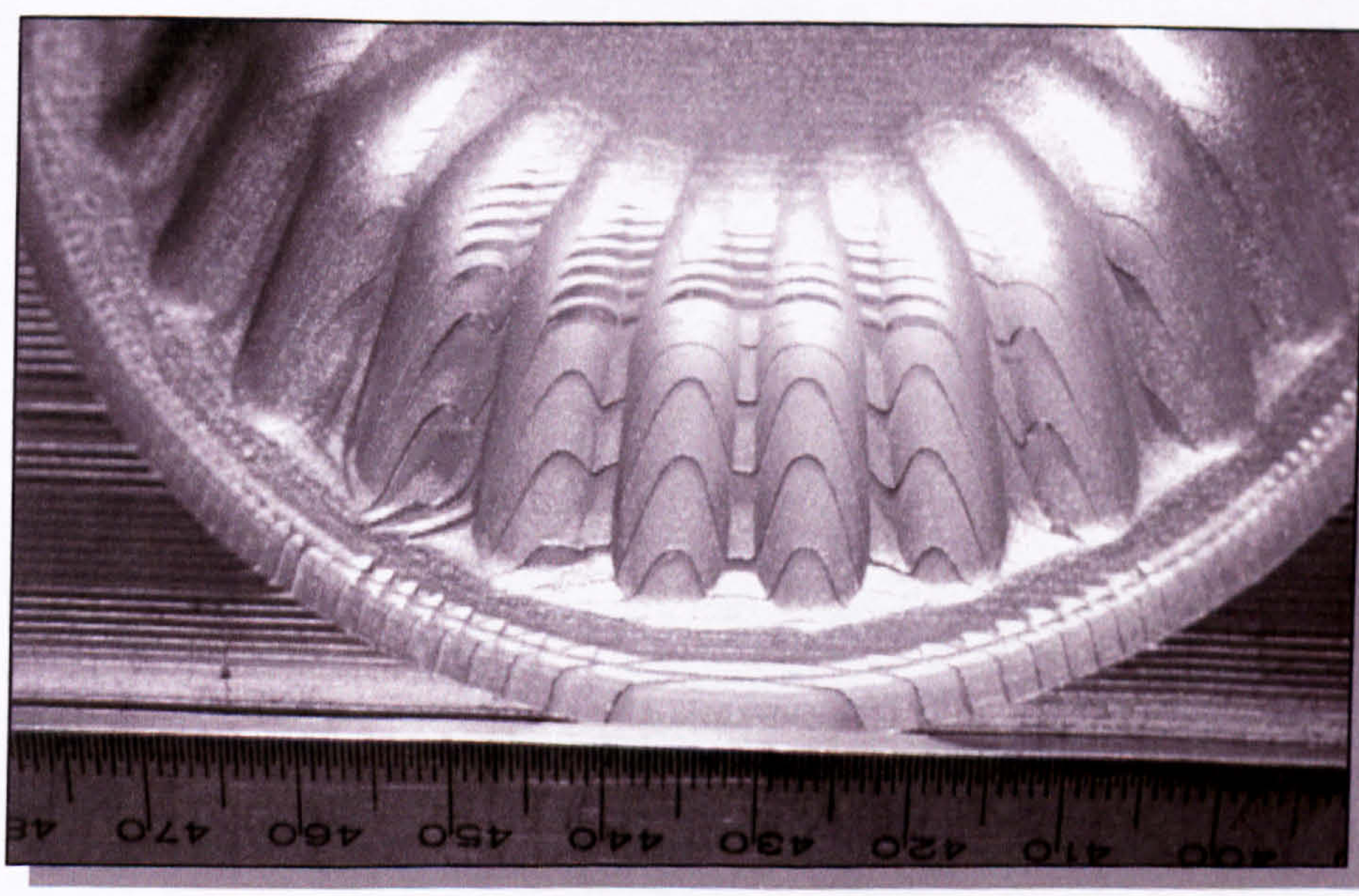

Figure 5: The laminate tool after EDM machining.

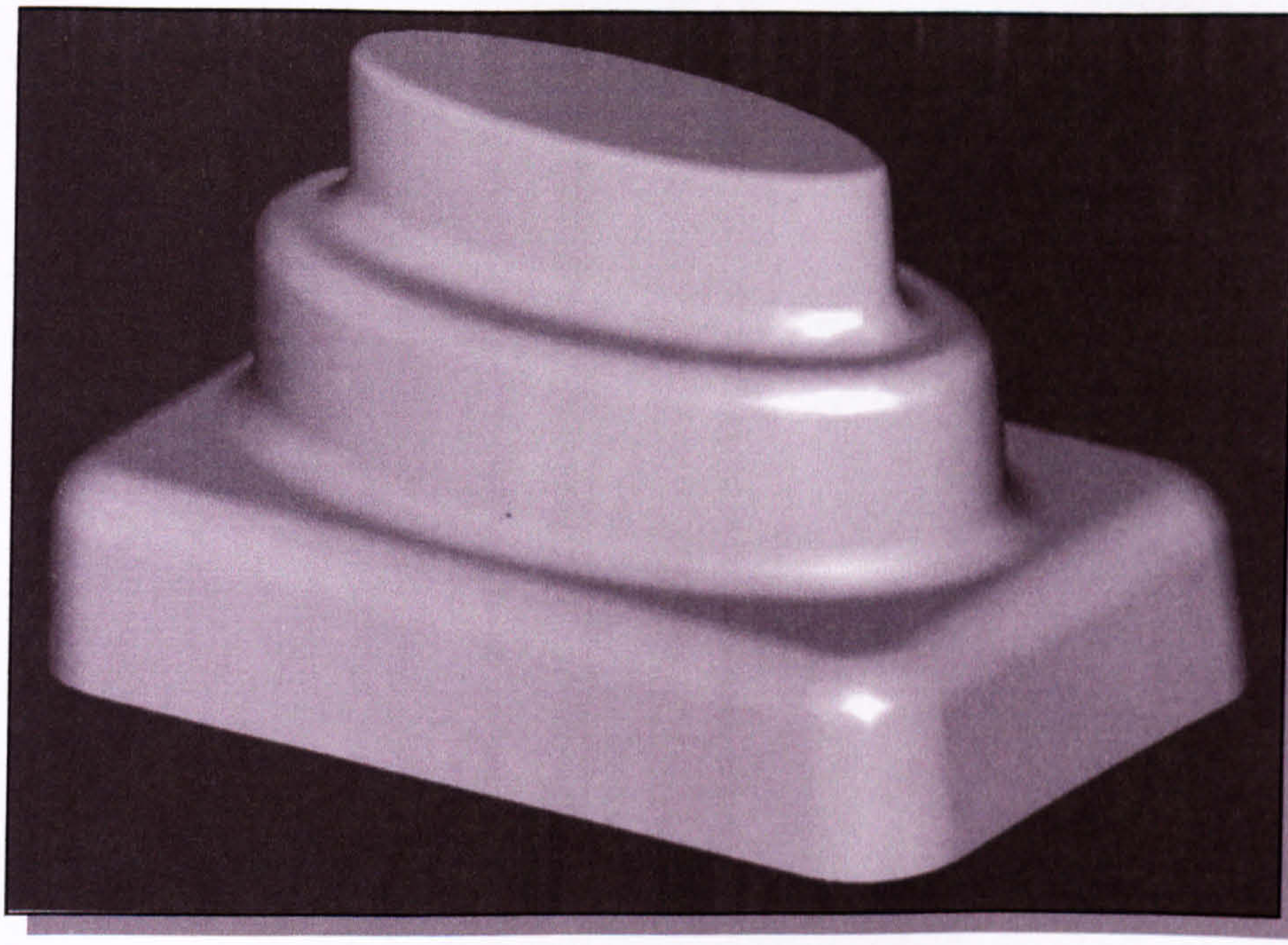

Figure 6: The initial CAD 'test' shape used as the basis for the Injection tool.

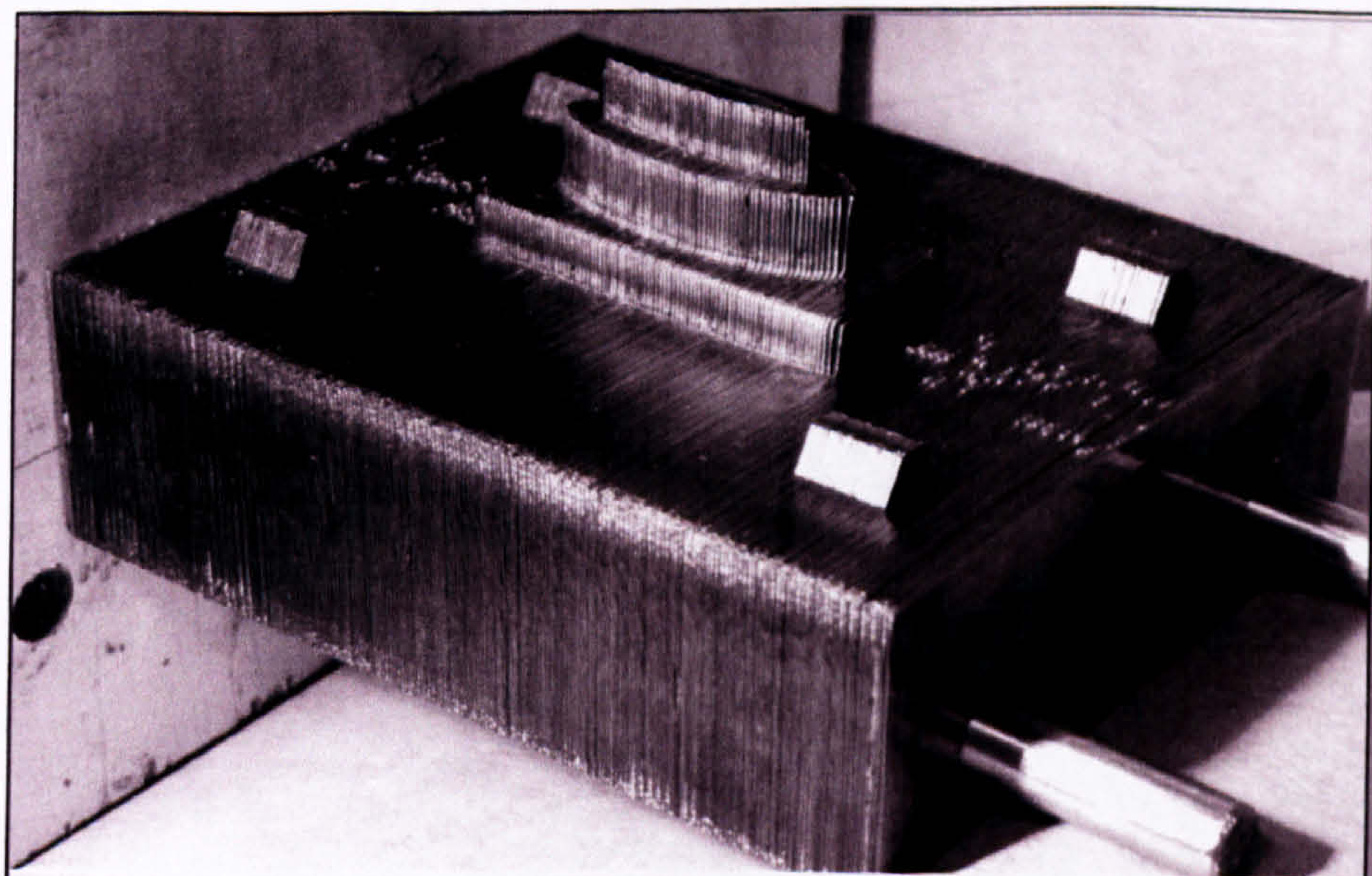

Figure 7: The tool showing the eliptical up-stand that justified 0.5mm steel.

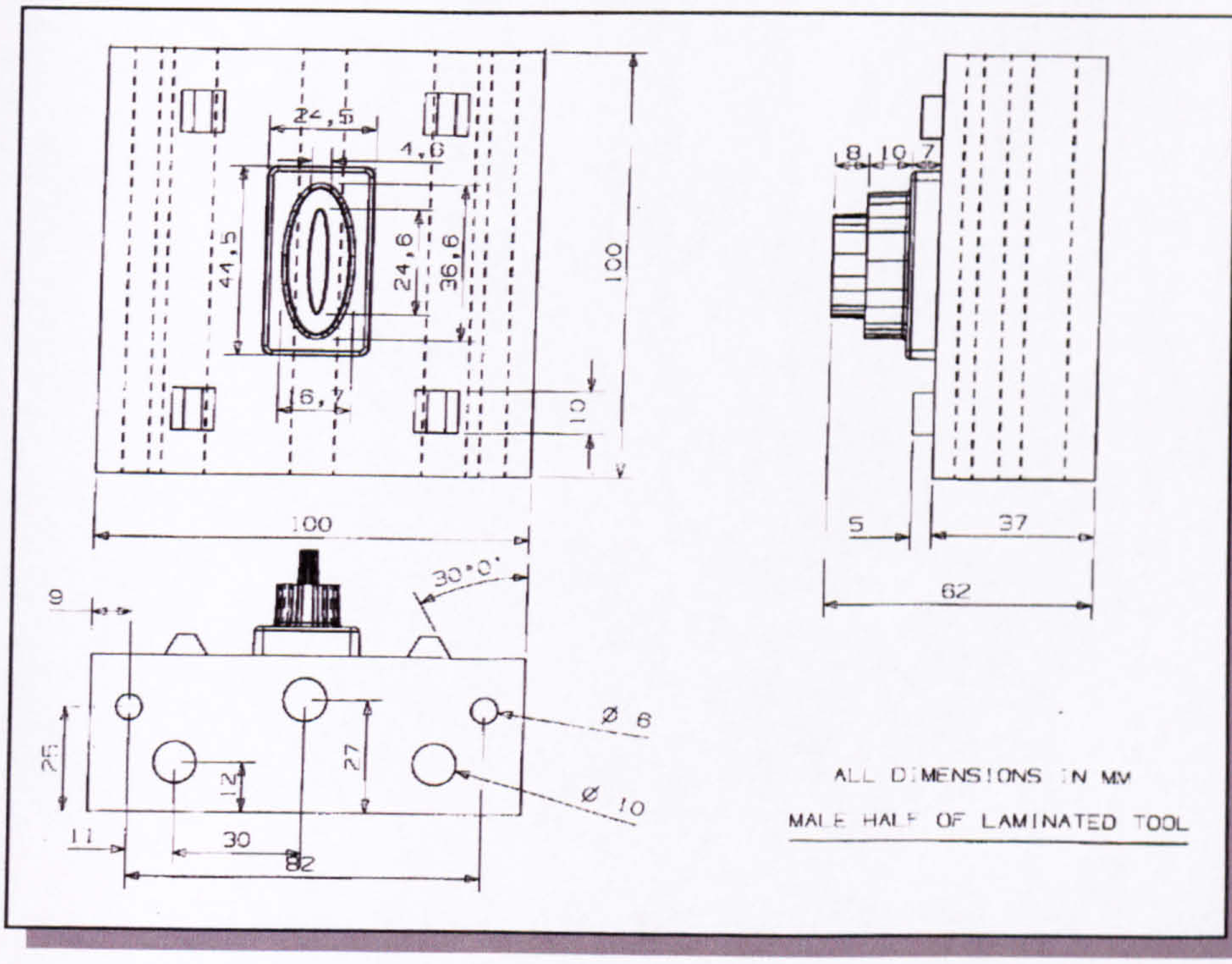

Figure 8: Schematic of the injection mould tool showing taurus.

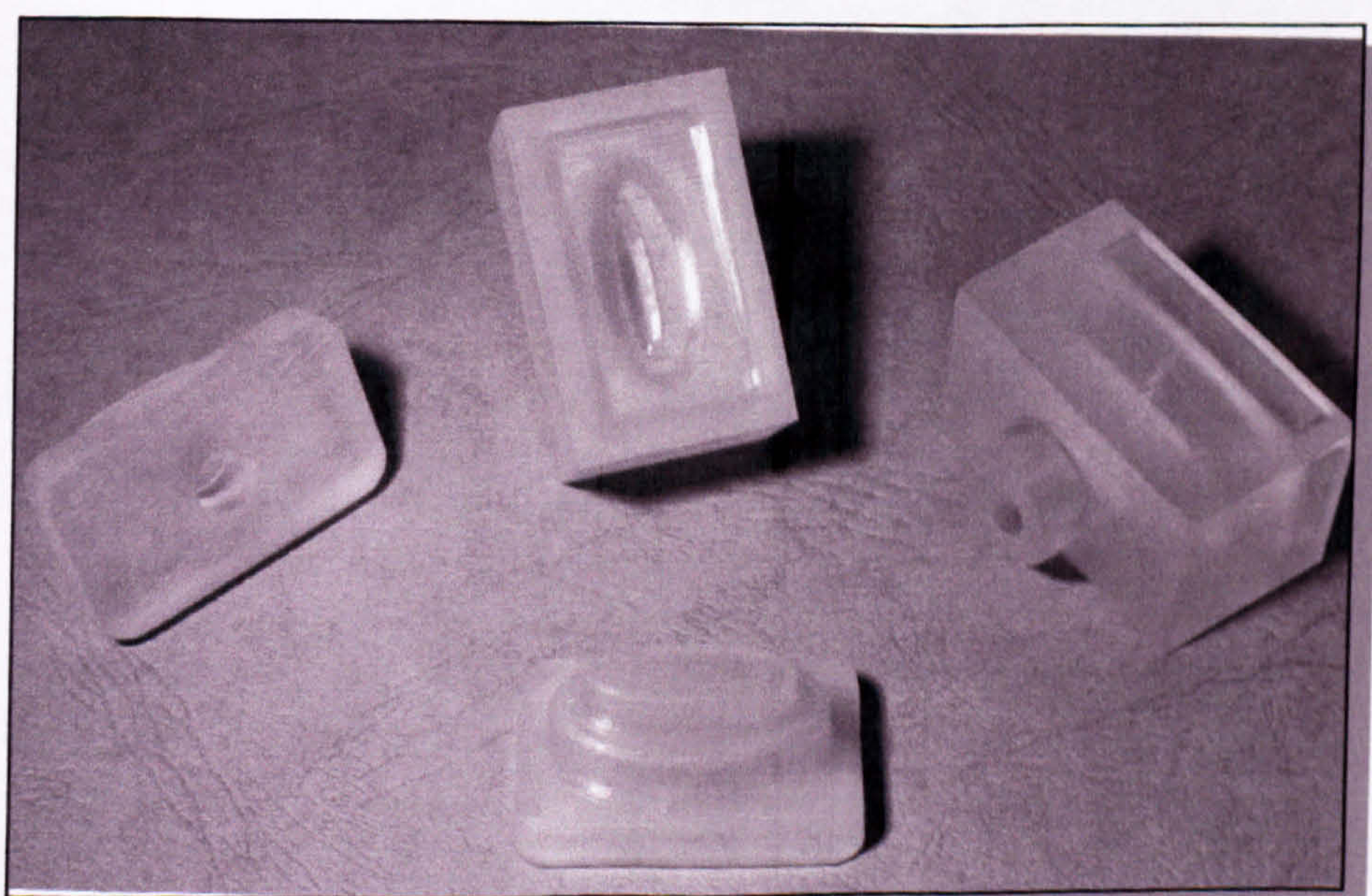

Figure 9: The SLA parts prior to electroplating.

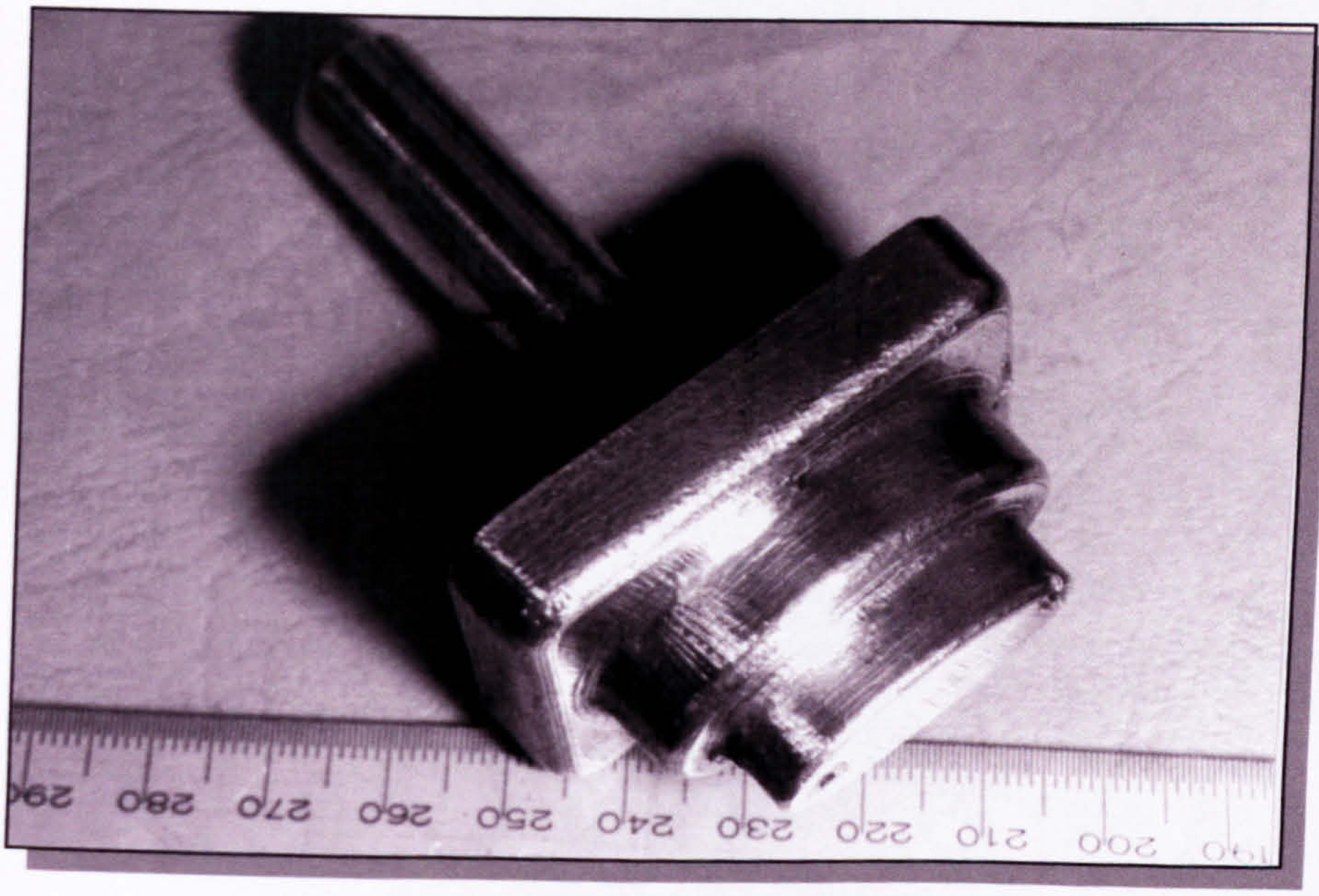

Figure 10a: The completed male electrode.

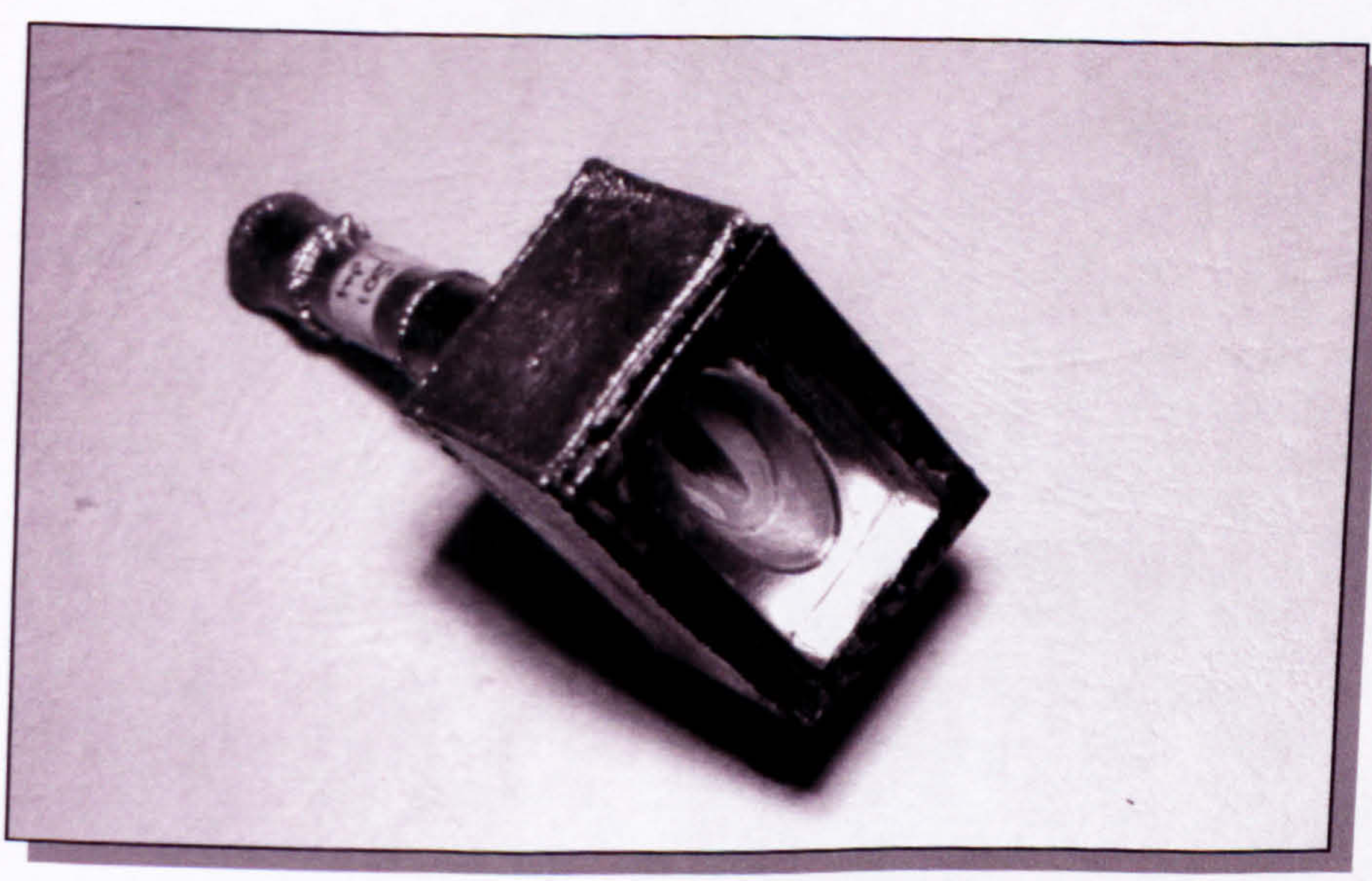

Figure10b: The completed female electrode.

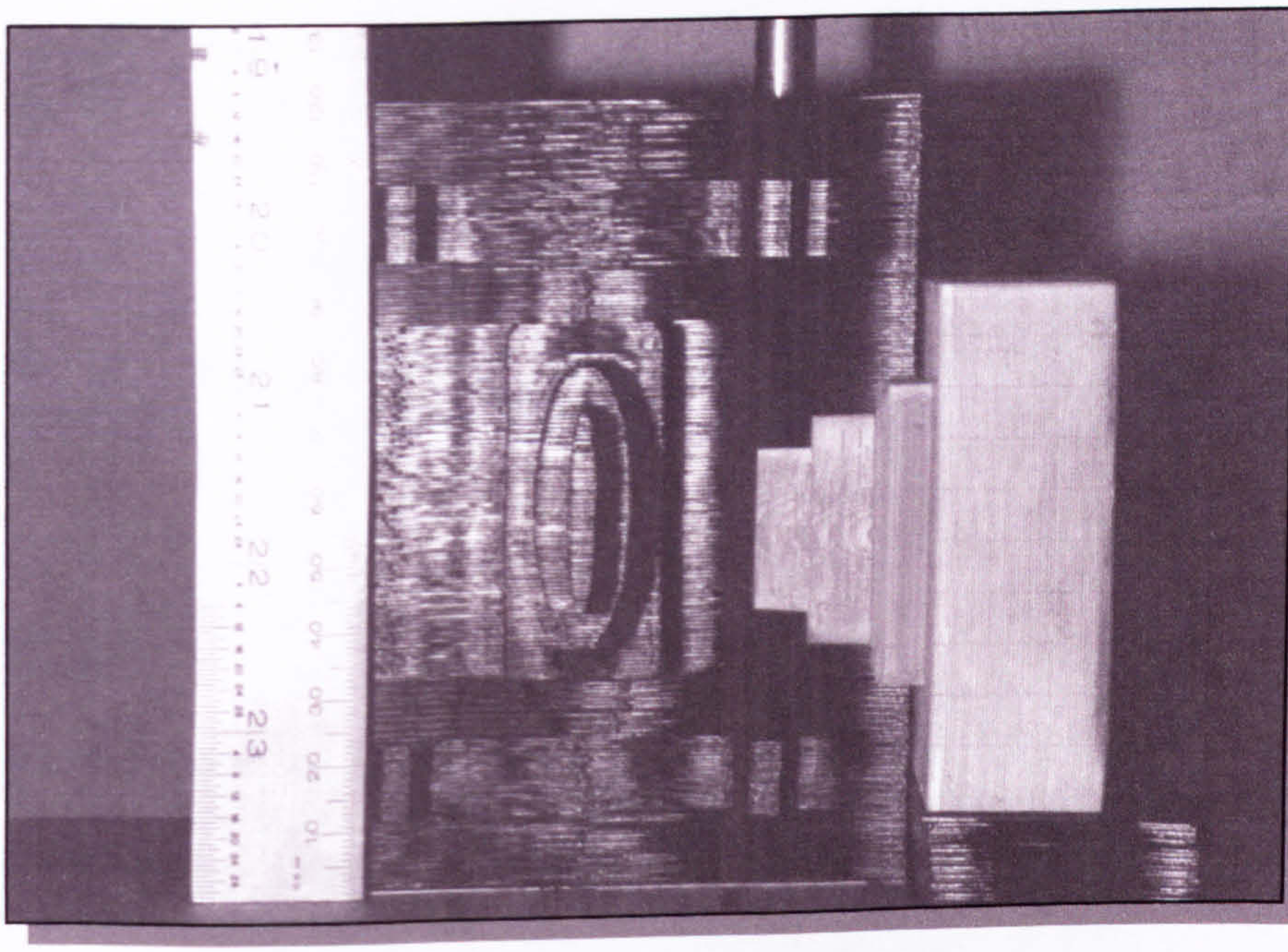

Figure 11: The deburred laminate tool prior to clamping.

Figure 12: The two halves of the tool showing the 'sparked' parting line.

Processing & Application of Rapid Prototyped Laminate Production Tooling

R.C.Soar, A.Arthur and P.M.Dickens

Presented at: The Second National Conference on Developments in Rapid Prototyping and Tooling, 18th-19th November 1996, at Buckingham College, UK, ed. by G.Bennett, pp 65-77.

ABSTRACT

One of the ultimate aims of Rapid Prototyping is the manufacture of production tooling, reducing lead times and costs from concept to product. Previous work by the authors has highlighted the potential for laminate production tooling from CAD data. This enables the user to prove the tooling design by rapid prototype modelling then use the slice file to laser cut sheet material which is assembled to generate the production tool.

The application of Laminate Tooling is currently limited by the poor surface finish of the assembled tool. This is created by a combination of stair stepping, caused by the angle of the laminate edge cut, and because it is not possible to obtain perfect alignment of laminates. Feasibility trials have been undertaken using electroplated Stereolithography (SL) models for Electro-Discharge Machining (EDM) finishing of the tool surfaces. This post-processing route provides an integrated fast-track-route to rapid products.

This paper outlines the principles of manufacture for laminate tooling and post process finishing. Examples of trials with product manufacture using laminate tooling are described. An appraisal of current research is presented with a discussion of commercial application.

INTRODUCTION

The materials available for the production of prototype parts are limited to those materials that the various RP processes can use to build the parts. In many cases designers want to build a prototype in the material that will ultimately be used in full production. This may be metals, glass, complex plastics, ceramics etc. To address this problem, research shifted to adapt RP to produce the moulds and tooling necessary to cast prototype parts into. It is this technology that is known as Rapid Tooling.

Various techniques have since been developed to realise this objective, all of which fall into two broad categories of 'indirect' and 'direct' tooling. Indirect tooling was developed as a means for the existing RP machine manufacturers to continue their dominance in the this new area. The indirect process involves taking an RP model, produced in SLA, SLS, LOM, BPM, Solider, etc. and use a secondary process to form the tool around it.

All the above processes are established, but recently industry has seen the emergence of direct tooling. Direct tooling requires the development of machinery and processes that can take layered data from a sliced CAD model and produce the tool in a suitable material that will allow the casting of a prototype in the ultimate material to be used. Examples of the research in this area include- 3D welding, Recursive Mask and Deposit (MD*) & Shape Deposition, Hexapod & multi-axis CNC machining, SLS of metal powders and Laminate tooling.

THE PRINCIPLES OF LAMINATE TOOL MANUFACTURE

The principle of Laminate Tooling is to take the sliced data of a metal tool, generated from a solid CAD model and output the slices to a CNC controlled profiling machine (laser, high definition plasma or abrasive waterjet). The slices are nested and a toolpath defined, after which the individual laminates are cut from a pre-determined thickness of sheet steel. The individual laminates are stacked and clamped together, in sequence, to give the tool that was defined by the original CAD model.

Laminate Tooling research began some fifteen years ago in Japan by Professor Takeo Nakagawa[1] (1977), [2] (1980), [3] (1981). So successful was this venture that in 1996 he reported that Hanai Engineering[4] in Japan had already produced their 10,000th laminate tool. To date, the feasibility of laminate tooling has been explored by various research groups around the world, including Glozer and Brevick[5] (!992), Schreiber and Clyens[6] (1993), Walcyk and Hardt[7] (1994), Lyett *et al* [8] (1995), and Dickens, Simon and Sketch[9] (1996), all with varying degrees of success. It is only within the past few years that world-wide interest in LT has peaked, primarily through the need for RT processes.

Even though the indirect processes can produce a good prototype of the part, in the material which will ultimately be used in production, none of them can produce a metal prototype tool. Only direct tooling can be run on the production machinery in order to test variables such as thermal transmittance, stress, flow of material, cooling efficiency etc.

After an initial pilot study with the production and post processing of a thermo-form laminate tool (Soar & Dickens[10], 1996) it was decided to go one step further with the production of an experimental injection moulding tool. With this tool it would be possible to test the efficiency of the laminate tool when subjected to high pressure, explore the potential for the inclusion of conformal cooling channels and post processing of the tool using a Stereolithography-EDM electrode.

The Generation of CAD Data for Laminate Cutting

The part to be produced from the laminate injection moulded tool, was 'solid' modelled in EDS Unigraphics. The profile of this part consisted of elements that would help assess the tool used to produce it. The part had a narrow internal detail, which would test the inter-laminar bonding on the male half of the tool. A varying curved surface would gauge the accuracy of the post processing operation and a flat top section, would check for any inaccuracies in laminate alignment.

With the part defined, the upper and lower surfaces of the model were separated at the parting line. These two surfaces would be used to form the two halves of the tool. The upper surface of the model was then used as a subtraction function from a solid block to form the female half of the tool. Likewise, the lower surface was used in the same manner to form the male half of the tool. The specification for these is shown below in Figure 1and 2:

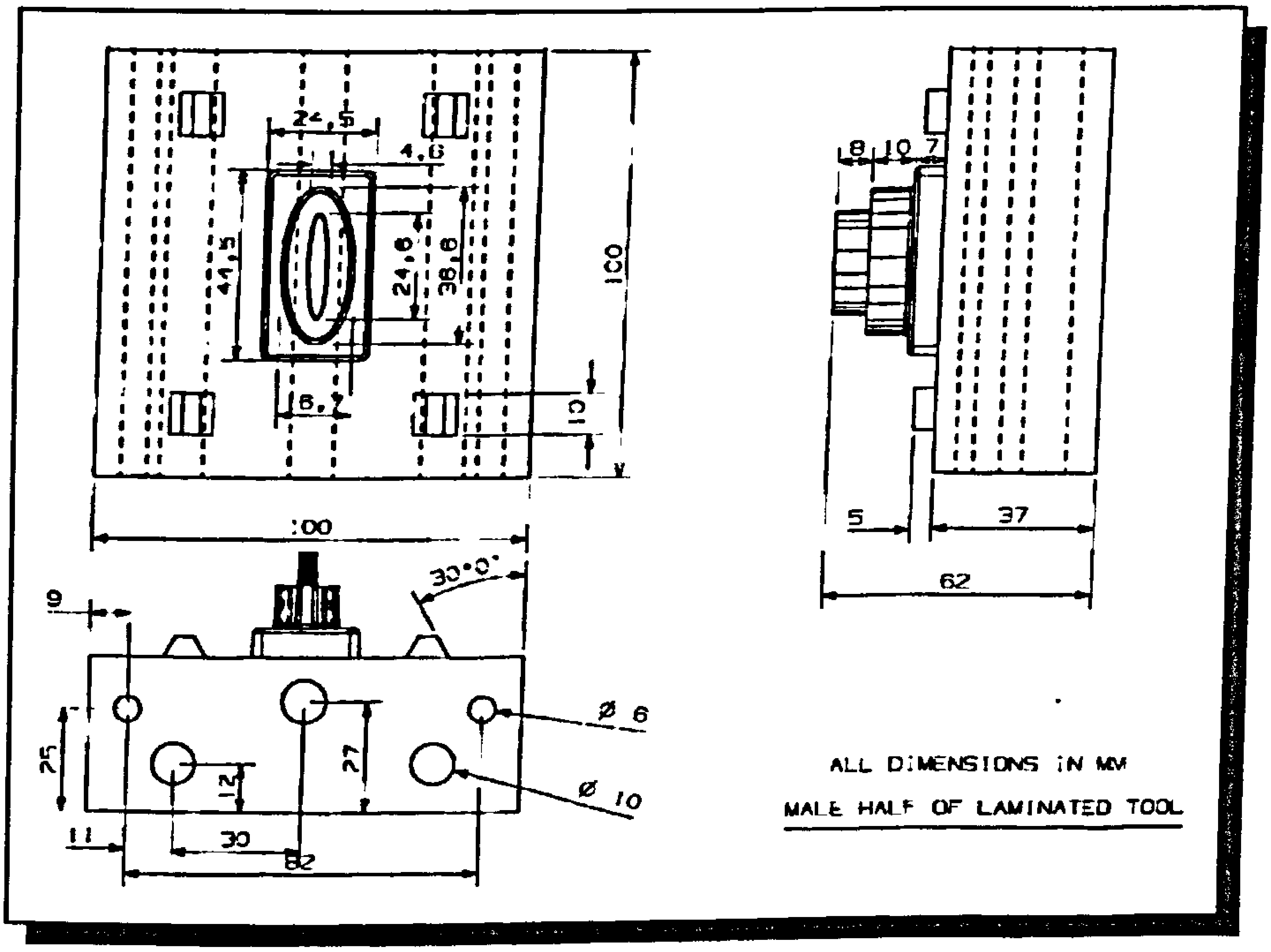

Figure 1 Specifications for the male half of the tool

Four through holes were defined in each half of the model which would used to bolt the laminates to 12mm thick end plates, and a conformal cooling channel for the female half of the tool. An offset of 0.5mm was added to the parting faces on both tools, so that both faces could be sparked together at a later stage to minimise any excess flash when the parts were moulded. Finally the locating pins were defined.

The next stage in the initial design was to slice the two halves to a pre-determined thickness in a given orientation. Due to the narrow up-stand in the male tool it was necessary to slice the tool vertically. The slice thickness had already been established as 0.5mm thick tempered and hardened CS70 carbon steel (450Vpn). This thickness would minimise the stepping in the tool and, therefore, minimise the EDM post-processing.

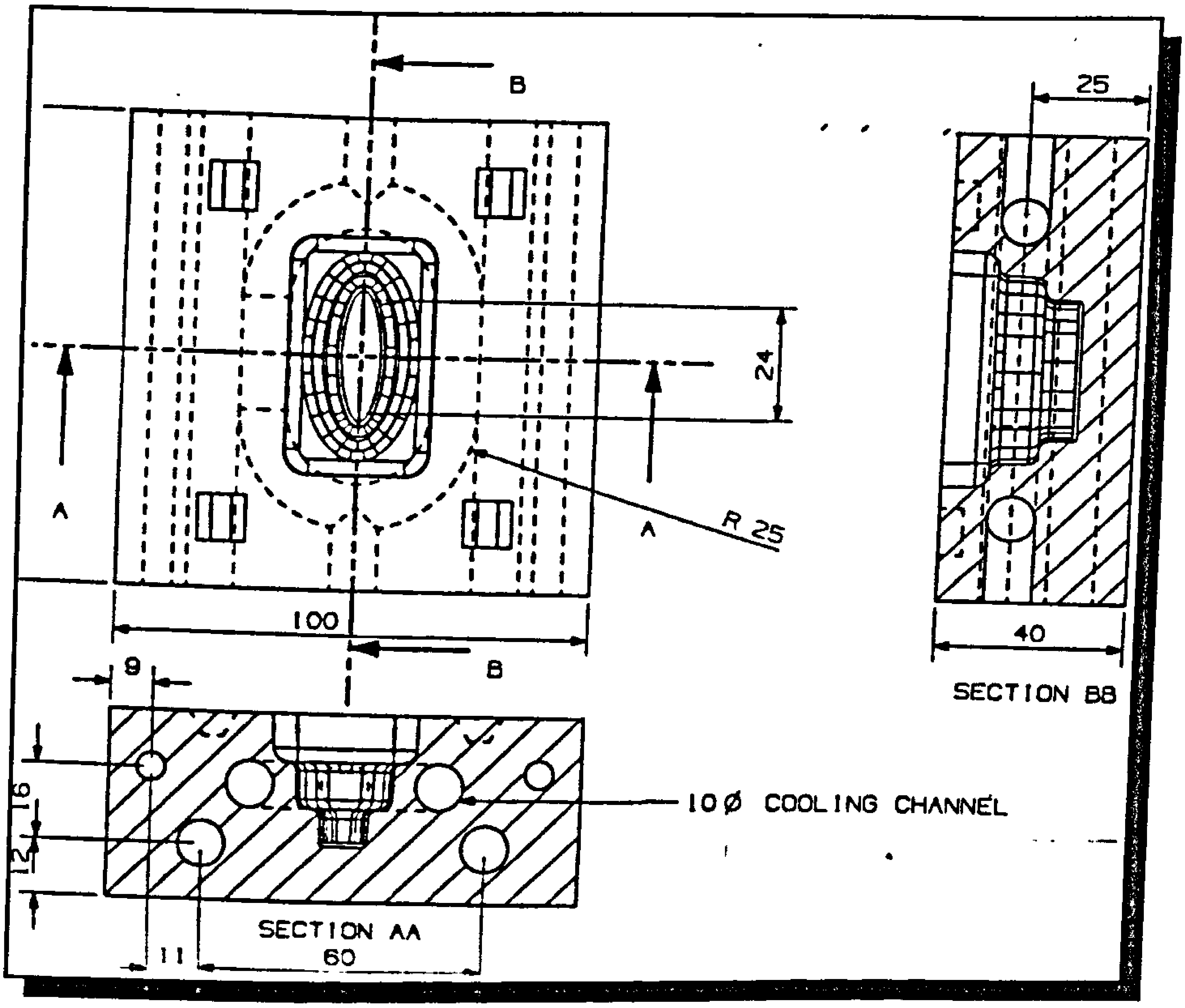

Figure 2 Specifications for the female half of the tool

It is important to note that the sheet steel had previously been purchased and delivered so that their mean deviation from the specified 0.5mm could be compensated for in the slicing operation. The actual deviation turned out to be 0.02mm. This implied that during the subsequent slicing of the CAD models the laminate thickness would be 0.52mm. A subroutine was created within the EDS software that would slice the model to a pre-determined thickness and output each slice to DXF. In addition, the model could be visualised in its sliced form to check for any inconsistencies.

Laser Cutting of the Laminates

The laminates were cut with CO_2 laser. Existing abrasive water jet as well as high definition plasma technology are not suitable, at present, for cutting sheet this thin and tend to be destructive. Cutting was done via a local sub-contractor with suitable facilities to process the 200 DXF files for each half of the tool. Before nesting and tool path definition can be carried out the subcontractor must be clear on the ordering and sequence of each laminate. For this project the sub-contractor was happy to ensure that the laminates were processed and cut in order and then marked with marker pen.

Total cost of cutting and de-burring the laminates was £1895.00 and the complete cutting operation including, nesting and tool path definition took 29 hours[20]. The breakdown is shown in Table 1.

Description	One off time(mins)	Quantity	Overall Time (mins)
Nesting of profiles into CNC	3	400	1200
Cutting the Profiles	0.5	800	400
Loading/unloading sheets	4	33	132
Total operation time: 1732 mins = 28 hours and 52 minutes			

Table 1. Breakdown of time taken to construct tool

Assembly of the Tool

Upon delivery of the laminates, they had to be cleaned to ensure that any grit between the laminates would not affect the overall width of the completed tool. Initial cleaning was done with a fine, wet and dry, emery paper by hand to remove any burrs left after laser cutting. This reduced the overall thickness of the clamped laminates from 125 mm to 120 mm. The laminates were then cleaned and degreased in an ultrasound bath in batches of twenty and the entire operation took 7 hours[20]. The breakdown is shown in Table 2.

Process	Time for one off (mins)	Quantity	Overall Time (mins)
Cleaning a batch of 2×20	5	20	100
Changing batches	3	20	60
Drying time	0.3	800	240
Total cleaning time : 400 minutes = 6 hours and 40 minutes			

Table 2. Breakdown of time to clean laminates for tool

This secondary cleaning was successful in removing almost all-surface contaminants. The final clamped thickness came down from 120mm to 105mm. To hold the laminates firmly and with minimal distortion, two end plates were machined through which the bolts would pass and allow a suitable clamping force of 15-20ft/lbs to the laminates.

For this study there was no inter-laminar bonding. One of the objectives was to see whether the tool would successfully operate as an injection mould tool without any ingress of material between the laminates when in use.

During the bolting of the laminates it was important to prevent the tools from distorting. This occurs as a clockwise pressure is applied to the laminates as the bolts are tightened. To prevent this, the tools were placed of a flat bed and butted up to an angle plate during tightening. Any distortion during tightening could be monitored and removed by twisting the tool in the opposite direction.

Once bolted, the tools had to be mated together to ensure that there was no flash along the parting line. This was done by sparking one half of the tool against the parting face of the other, until the 0.5mm offset that was incorporated at the design stage was removed. Sparking the two halves of the tool together also assisted in bedding the locating pins into place. The finished tool is shown below in Figure 3, along with the inlet port that was also sparked with the two halves of the tool clamped together.

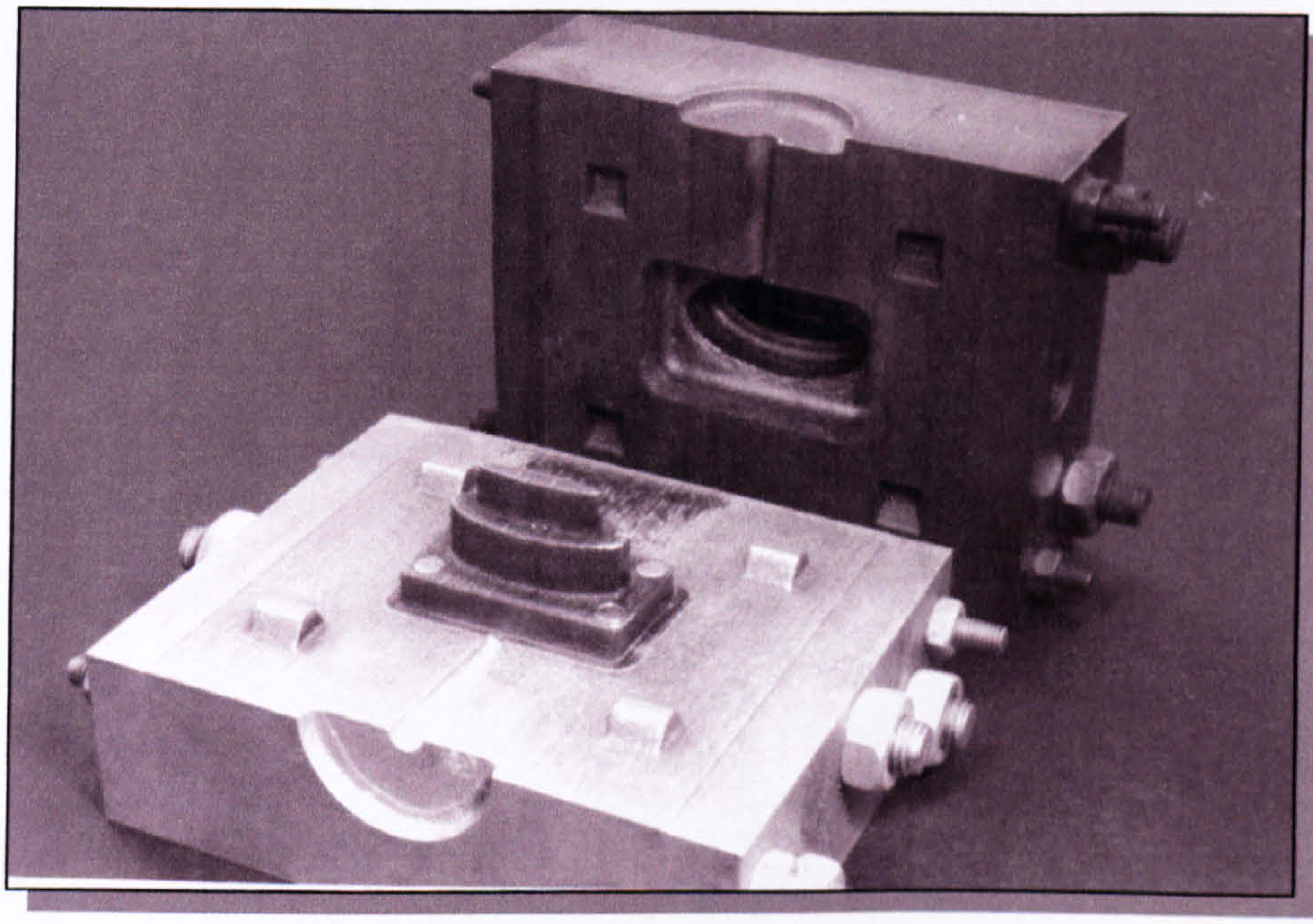

Figure 3. Finished laminate injection mould tool

Injection Moulding with the Tool

To test the effectiveness of the tool without any secondary finishing operation, the tool was run on an SP injection moulding unit within the Department. This would show firstly, the surface finish possible on the moulded parts without any of the stepping that occurs in a laminate tool being removed. Secondly, there were initially concerns that the vertical up-stands on the male laminate tool would not be sufficiently clamped and thus would allow the ingress of polymer between the laminates, preventing the removal of the parts from the mould.

The polymer used was polypropylene. This material is a commonly used injection polymer with rapid setting times and uniform shrinkage. To ensure that the part could be removed once set, it was necessary to include ejector pins in the male half of the tool as the parts would shrink around the up-stand.

The chamber was pre-heated to 180^0C and the pressure compressed air pressure was set at 40psi. The conformal cooling channel was not used as only 25 shots were being taken. All the parts produced from the mould were of high quality with little stepping visible as seen in Figure 4:

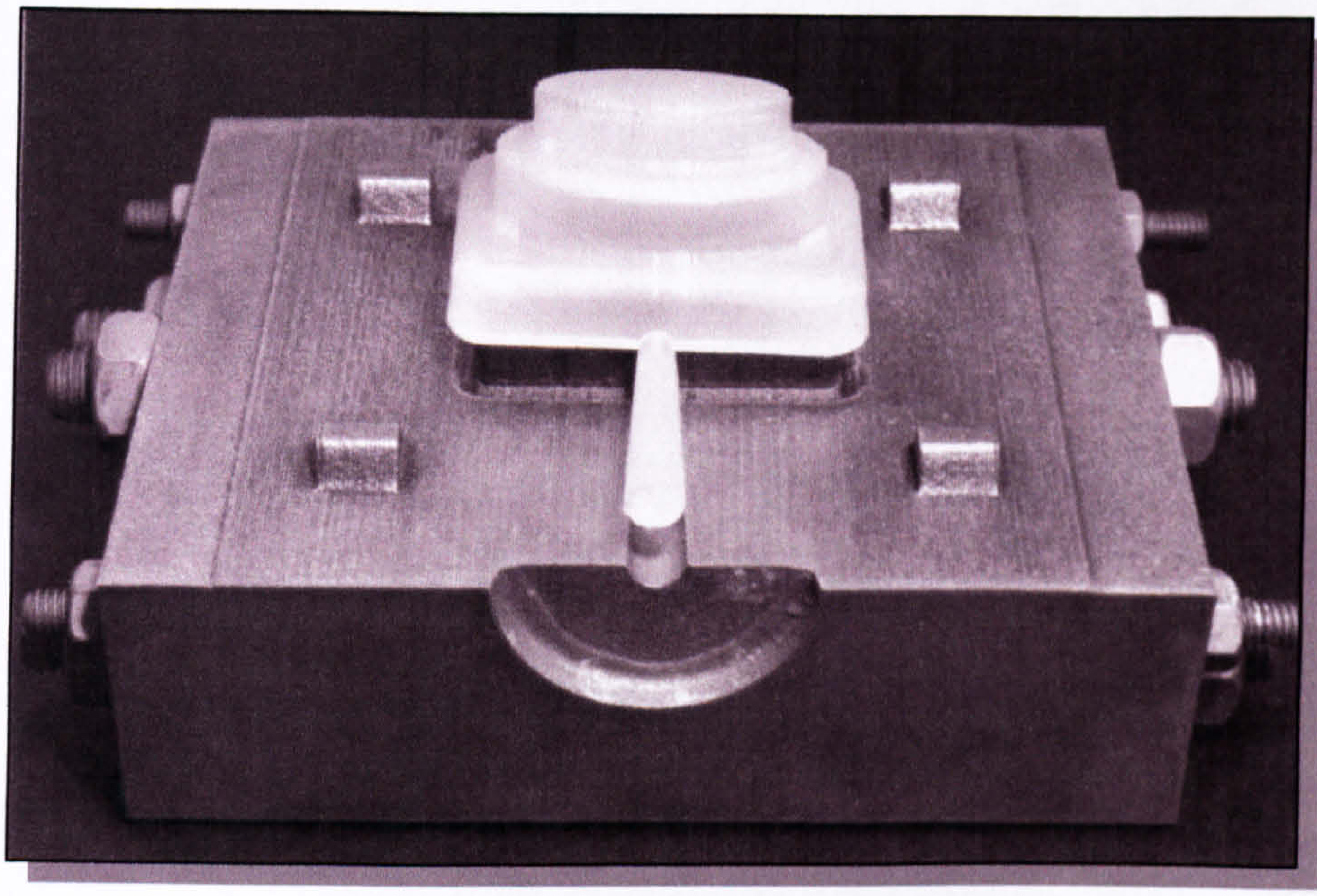

Figure 4. Moulded part from the laminate tool

Satisfied that this was successful, the compressed air pressure was raised to its maximum of 85psi. This was enough to give a gate pressure of 2,775psi. The chamber was pre-heated to 220^0C and the tool run until it became so hot that the polymer could not set in the tool. Again no polymer ingress was observed even though at these temperatures the polymer had a very low viscosity.

POST PROCESS FINISHING OF ASSEMBLED TOOL

Stair-stepping is a function of the slicing of the CAD representation and is more pronounced on curved surfaces and shallow angled planes. Vertical planes (0° to the cut angle) are not susceptible to this stepping, however it is these surfaces which are most affected by any misalignment of laminates when stacked for assembly. Both the stair stepping and the misalignment can be eradicated by surface finishing. Where tools are complex or include deep recesses it may not be possible or practical to hand finish the internal surfaces.

One technique which can be applied to finishing is Electro-Discharge Machining (EDM), but complex electrodes can be costly with unacceptably long lead times. By rapid prototyping an electrode from common data its manufacture can be undertaken concurrently with the laminate cutting operation. EDM in the form of die sinking is used extensively for surface treatment or modification of tooling[11] (Masui *et al,* 1995), [12] (Mohri *et al*, 1993), [13] (Shunmugan *et al,* 1994). It is far easier to texture or profile a copper electrode than to work on tool steel.

As a finishing operation, the machine operator can choose from a number of set-ups which generate different degrees of surface roughness. The set-up determines the intensity of spark emission which in turn generates a specific 'spark gap' and surface finish. The spark gap is the difference between the size of electrode and the size of eroded cavity. To allow for this gap dimension the electrode must be undersized accordingly, therefore selection of machine set-up needs to be made before electrode manufacture with respect to this and the desired surface finish..

SL Models as EDM Electrodes

At the University of Nottingham a technique has been developed for the manufacture of EDM electrodes from rapid prototyped Stereolithography (SL) models[14] (Arthur & Dickens, 1995), [15](Arthur & Dickens, 1996), [16](Arthur & Dickens, 1996). For this process the original CAD model of the part is used. As before, the upper and lower surface of the model are separated and it is these that ultimately become the two electrodes used to spark the two halves of the tool. An offset was defined on both faces of the electrodes to account for 15μm of a coating of high conductive silver paint, 175μm of electroplated acid copper and the required spark gap of 0.18mm.

Investigations have determined an optimum copper thickness of 175μm, balancing the geometric limitations with achieving efficient machining rates. If a coating is too thin it will suffer premature failure[17](Arthur *et al*, 1996), but thick deposits can compromise the geometric definition of the SL model. Through a programme of parametric optimisation a material removal rate (MRR) commensurate with that of a standard EDM finishing operation have been achieved.

Both CAD models are then produced as Stereolithography parts and treated as above. The results can be seen in Figure 5:

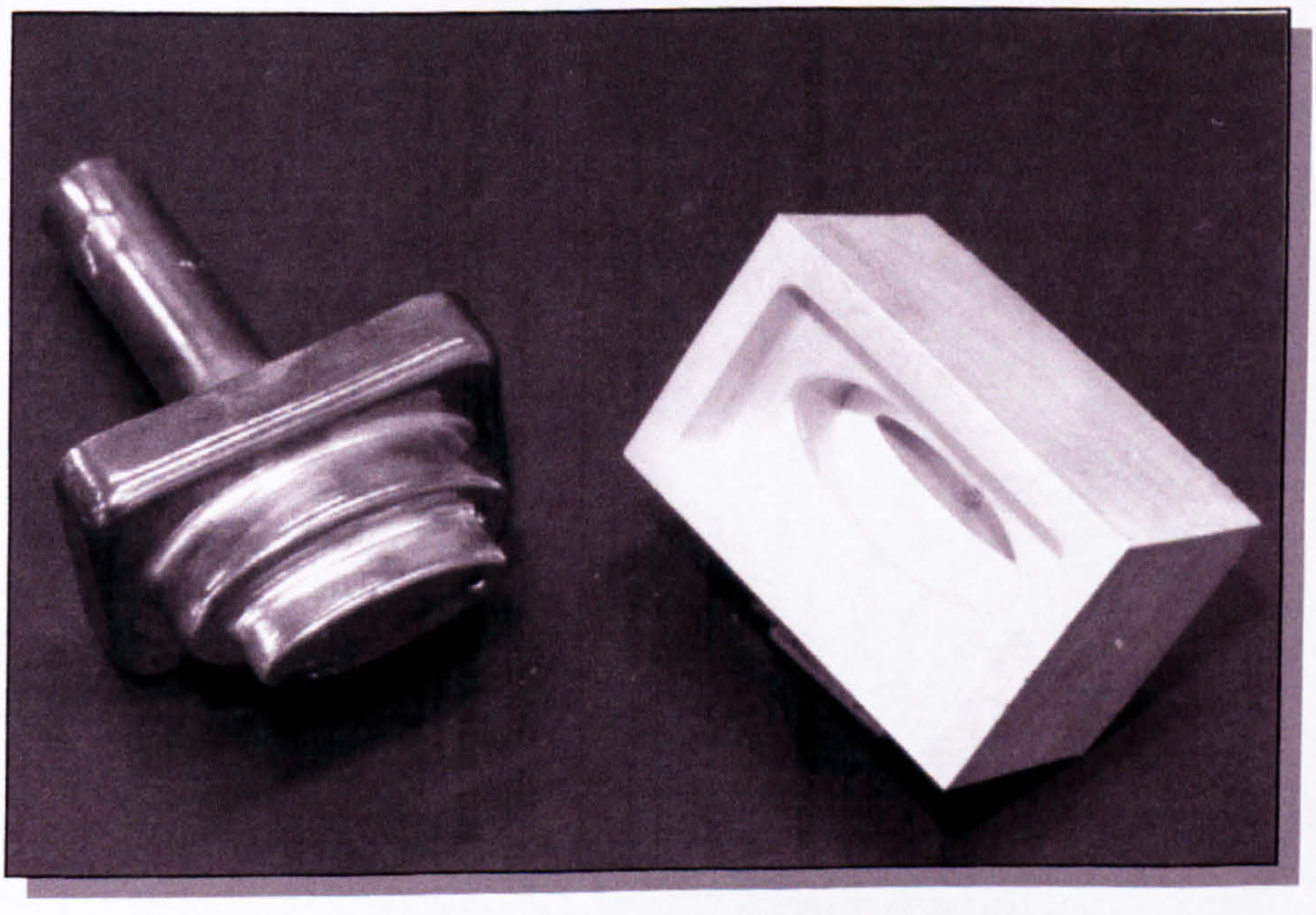

Figure 5. The completed SLA-EDM electrode

On completion of the electroplating process, it was clear that the female electrode could not be plated evenly. The concave recess proved too deep in which to throw the electrolyte and now forms the basis for further work with GEC to modify the electrolyte. The male electrode had an even coat of copper over its entire surface and was used to spark the female half of the laminate tool. Two hours into the sparking operation this electrode failed. The point of failure was on the sharp internal corner of the electrode where excessive heat built up. Subsequent attempts to produce more electrodes with thicker deposits also failed, but not without most of the sparking complete.

Current Limitations Associated with the Finishing Operation

SL model electrodes of simple geometries have been used successfully to erode cavities in tool steel, described above. Premature electrode failure has been observed on convex curved surfaces. This is initiated as delamination of the copper coating from the SL model, ultimately resulting in tear or rupture of the copper. Delamination of the copper can cause irreparable damage to the laminate tooling as the deformed electrode profile is replicated on the tool surface. The failure mechanism is currently being investigated and efforts are being made to eradicate this problem.

As an alternative to using SL models directly as EDM electrodes a 'negative' of the model can be produced and a copper electro-formed shell generated from this master. The advantage of this approach is the thickness of deposit which can be built up, without compromising the electrode geometry[18] (Arthur, Cobb & Dickens, 1996). The electro-forming process can have lead times of several days dependant on geometry of the master and shell thickness required. The use of electro-forming overcomes the problems associated with electrode failure by delamination but some geometric features are difficult to form.

CONCLUSIONS & FURTHER WORK

This ongoing research has shown that the production of fast, cheap injection mould tooling is possible with little or no inter-laminar bonding. Within a week, a prototype tool can be built directly from a CAD model that can then be run on production equipment. Conformal cooling channels are easily accommodated for, enhancing the performance of the tool. As far as the removal of stair steps, then more work is required. Initial work[18] (Soar & Dickens, 1996) has shown that it can be done, but there appear to be serious limitations to the 'direct' electrode approach. Work now continues to pursue the 'indirect' electrode approach.

The experimental tools discussed here are not representative of a production laminate tool. Laminate tooling is far better suited to larger tooling, typically from 0.5 cubic metres upwards. If a tool is too small, then it becomes difficult to clamp and bolt. Work is already under-way to develop prototype laminate tooling for four multinational companies. All are in the field of pressure die-casting and this work will form the basis of future papers.

Future research in Laminate Tooling will look at : -

- Inter-laminar bonding using resins, pastes, welding, diffusion etc. to eliminate the need for bolts and clamps.
- Laminate orientation and exchangeable inserts.
- Optimum design of conformal cooling channels for laminate tooling.

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Design of Laminate Tooling for High Pressure Die-casting

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ABSTRACT

Over the last three years research at the Centre for Rapid Prototyping at the University of Nottingham has been focusing on the developing field of Rapid Tooling. Within this area we have been investigating the production of Laminate Tooling. This paper outlines the work that has been carried out to develop Laminate Tooling for automotive pressure die-casting applications on behalf of the United States Council for Automotive Research (USCAR).

INTRODUCTION

Initial research into the production of laminate tooling at the University of Nottingham by Dickens, Simon & Sketch[1] revolved around the production of simple laminate tooling for large-scale, low-pressure moulding applications. This work was then extended to thermo-form tooling and, latterly, injection mould tooling [2].
This paper shows the development of laminate tools for pressure die-casting in a three stage exercise. The first stage was to produce samples for thermal fatigue testing. The second stage was to produce a small die insert that could be run on conventional die-cast machinery, and the third stage will be to construct a full-scale pressure die-cast tool for the production of transmission housings. For this paper, the first and second stage will be covered, showing the decisions and research undertaken.

ADVANTAGES OF LAMINATE TOOLING

The principle of Laminate Tooling (LT) is to take the layered data of a tool, generated from a solid CAD model and output the slices to a CNC controlled profiling machine (laser, high definition plasma or abrasive waterjet). The slices are nested and a tool-path defined, after which the individual laminates are cut from a pre-determined thickness of sheet steel. The individual laminates are then stacked and clamped together, in sequence, to give the tool that was defined by the original CAD model.

Laminate Tooling research began some fifteen years ago in Japan by Professor Takeo Nakagawa[3]. So successful was this venture that in 1996 he reported that the Hanai Engineering Company[4] in Japan had already produced their 10,000th laminate tool. To date, the feasibility of laminate tooling has been explored by various research groups around the world, including Glozer and Brevick [5], Schreiber and Clyens [6], Walcyk and Hardt [7], Lyett *et al* [8], all with varying degrees of success. It is only within the past few years that world-wide interest in LT has peaked, primarily through the need for rapid tooling processes.

At present there are only a couple of well-established techniques that serve as prototyping methods for die-cast parts. These are the investment casting and plaster cast moulding processes. By using these techniques the manufacturer is limited by the following factors:

- No mould is produced that can be run on the die-cast machinery
- The mould is wasted after every cast
- Pouring molten metal cannot simulate the pressurised operation in die-casting.
- Parts cannot be fully tested as grain structures differ from that of a die-cast part
- Cooling of the tool through the incorporation of cooling channels cannot be tested
- Parts tend to have a poor finish

Soar & Dickens [9] have shown that laminate tooling offers a fast and cost effective way by which metal tools can be produced directly from a 3D CAD model. This simple process results in a tool with the following advantages:

- The inclusion of conformal cooling channels with any cross sectional shape
- Ease of disassembly for alteration
- Easy replacement of damaged or worn elements
- Exceptionally large tools (laser can cut profiles up-to three metres by two metres)
- Direct production of the tool from a CAD model

LAMINATE ORIENTATION

On receipt of the CAD data files, the model was loaded into EDS Unigraphics via DXF. Figure 1, shows the solid model with overall dimensions of 4" by 4" by 3". The first step in the process was to define which way the laminates would ultimately be assembled. The tool was to fit in a pre-formed bolster and receive several thousand shots to establish its performance. The parameters under which the tool would be operating are shown in Table 1:

Max. Temperature	1350^{0}F (746^{0}C)
Cavity Pressure	12,000 lbs/ ins^{2} (82.74 MPa)
Gate Velocity	Min 1800 ins/sec (45.72 m/ sec) Max. 2300 ins/sec (58.42 m/ sec)
Tool Life	Min 3,000 shots

Table 1. Operating parameters for USCAR tool

Even with cooling, the average temperature in the tool will be around 425^{0}C (797^{0}F), rising to 600^{0}C (1112^{0}F) where 'hot-spots' occur. The material to be cast was Aluminium 383.3. At this stage the main concern was how the pressure within the tool would act on individual laminates. Up-to this point, the laminate tools produced for other applications all had vertically orientated laminates, or laminates perpendicular to the parting line. However, there was concern that at these elevated pressures and temperatures, the laminates that formed the features could be forced apart due to the ingress of molten metal. With this tool it was decided to orient the laminates horizontally or parallel to the parting line, and use solid inserts (cast or machined) from tool steel to replace laminate features.

The second reason for horizontal orientation was due to the two large through holes present in the top of the model which indicated clamping points to attach to the bolster. With clamping pressure being exerted in this direction it made sense to orient the laminates perpendicular to this force. The last reason for horizontal orientation was for ease of manufacture. Within all the laminate tools previously produced it has been necessary to produce thick metal end plates.

The main role of the end plates is to constrain the laminates and prevent warping. In line with this, it was decided to wire EDM the top part of the tool from solid stock, create two more bolting points, and a bottom end plate. Therefore, the excess heat that would be generated as molten aluminium passed through the inlet gate would be dissipated evenly without distorting the laminates below. The end plates were defined from the CAD model and stored as a separate file, as shown in Figure 2.

DESIGN OF THE INSERTS

Laminate Tooling is ideally suited to the inclusion of solid inserts into the assembly. In conventional tooling, inserts are incorporated by boring a blind hole into the tool and the insert is then positioned through the use of a peg. With laminate tooling it is possible to create the insert with the addition of a 'foot' which holds the insert firmly in place once the tool is assembled.

Within the CAD model the insert is isolated and extended down so that it passes through the first few laminates in the stack. The 'foot' is then created at the base of the insert so that it is trapped in place by the laminates above it. The inserts are shown in Figure 3 and were produced as Stereolithography parts as a demonstration of how the tool would be constructed.

MATERIALS SELECTION

Before a suitable material was chosen the first stage was to specify the thickness of the sheet metal required. Choosing a suitable thickness not only affects the laser cutting of the laminates but also the quantity of metal to be ordered. A subroutine had been previously generated to slice the CAD representation of the tool to a predetermined layer thickness. Each slice represents an individual laminate and also represents the tool path that the laser will use to cut the sheet metal.

Previous research has shown the optimum thickness of sheet material for mould tooling is around one millimetre, as this gives reasonable definition to the tool with minimum secondary finishing necessary. The software sliced the model and output each slice to DXF ready for transfer to the laser profiler. It is worth noting that the DXF files should not be used to cut the sheet metal until the mean thickness of the delivered material has been measured and compared to the specified sheet thickness. Any increase or decrease in thickness must be compensated for when slicing the CAD model. Figure 4, shows the sliced CAD model, once the end-plates had been subtracted, prior to conversion to DXF.

Not only is the selection and specifications of the sheet material one of the most critical choices to be made it was also one of the hardest choices to make due to availability of suitable material. As the tool was to be inserted into a bolster prior to testing, it was essential to ensure compatibility between the material used for both. In the UK, cold rolled tool steel is not readily available. Nakagawa[10] has previously constructed laminate tools from such material due to its availability in Japan. On a large scale, it would be feasible to import rolled tool steel, but for this research it was decided to find an alternative material that would match the specifications laid down. The material specifications for the insert are shown below and are similar to tool steel:

Material Hardness	Min 36 Rockwell C Max. 45 Rockwell C
Thermal Conductivity	16.5 BTU/FT.H. ^{0}F @ 420^{0}F (215^{0}C)
Thermal Expansion	Max. value 6.4 mic.in/in @ 400^{0}F or 11.5 mic.m/m @ 204^{0}C Max. value 7.3 mic.in/in @ 1200^{0}F or 13.12 mic.m/m @ 649^{0}C
Machinability	Comparable to H-13 at 42R_C
Microfinish	Max. value = 120 mic.in (0.3 μm)
Heat Checking	No cracks greater than 0.020" (0.5 mm) depth after 3000 shots

Table 2. Specifications for material used in the USCAR project

The most readily available cold rolled sheet metal in the UK is the CSxx grade material. This material has been successfully used for laminate injection mould tooling in the past. The CS classification is followed by a figure that represents the percentage carbon present in the steel. To achieve the specified hardness for the material, samples of CS70 strip were assessed (0.7% Carbon), the equivalent AISI-SAE grade is 1070. This was flattened and hardened to 415/435VPN or 42/43Rockwell C. The coefficient of thermal expansion for this material was 6.394 mic.in/in @ 400^{0}F and 7.394 mic.in/in @ 1200^{0}F which just fell into the specified range.

It was important to establish what effect the molten aluminium would have on the hardness of the metal sheets. To test this 50mm by 50mm samples were cut from the sheet and submerged or 'dunked' in molten aluminium for ten seconds. This represented a worst case scenario that the steel could be subjected to when in use. The results of this test are shown in Table 3:

Individual 10 Kg VPN Readings					Av. VPN Reading	Av. Rockwell C
Sample 1	308	333	308	306	**318**	**32**
Sample 2	265	265	265	262	**264**	**25**

Table 3. Hardness readings from material samples

If the CS70 laminates were allowed to heat up to the maximum operating temperature of the tool they would anneal to well below the specified hardness range. The average temperature within a die-cast tool falls below the annealing temperature of CS70, but it was hard to know what might happen to the steel where hot-spots occur within the tool. The laminate tools will be subjected to thermal fatigue testing. A standard test measures the degree of thermal cracking or fatigue that appears on the surface of the tool when subject to constant thermal cycling and shock. The actual sample submitted is shown in Figure 5, two 1.5" (38.1mm) thick end-plates constrain the laminates within the measurement zone.

The measurement zone is a section 3" (75mm) long on the corners, equidistant from each end. Any cracking pattern is reported as the average maximum crack length and the summation of the squares of the crack length for each corner. The more severe the crack pattern, the lower the thermal fatigue resistance of the material. The results closely correlate with behaviour of dies in industry. The test consists of dipping the sample laminate tool into molten aluminium for 12 seconds, withdrawing it and then spraying it with lubricant between 'dunks'. Each sample is a 2" (50mm) by 2" (50mm) by 7" (177.8mm) rectangular parallel piped specimen with a 1.5" (38.1mm) diameter hole in the centre for internal water cooling. The four corners have a constant 0.010" (0.25 mm) radius that intensifies the predominantly uniaxial stress at the measurement area. The sample is mounted on a rig that allows for submersion in a bath of molten aluminium at 1350^{0}F (732.2^{0}C) for 12 seconds after which it is then removed for 22 seconds. During this procedure, water flows through the central hole at a rate of 85 gallons/ min (386.4 litres/ min.). Measurement of cracking is measured after 5000, 10,000 and 15,000 cycles.

The results of this test are not yet available for publication, but due to the concerns that CS70 would be unsuitable, a further search is underway to establish sheet material with better properties such as AISI-SAE 4340 or EN24.

INTER-LAMINAR BONDING

With earlier laminate tools, for low-pressure applications, it was enough to bolt the laminates together and this was the principal reason for the end plates being used. With injection moulding tools, epoxy resins were used to bond the laminates together. The best solution was ultimately found to be a combination of physical bolting and resin bonding. Inter-laminar bonding overcomes the problem of up-stands where bolting, alone, cannot apply enough force. In this die the excessive heat and forces meant inter-laminar bonding would be essential so that the laminate tool would perform as a solid tool, which bolting alone could not achieve. Whatever the bonding medium, it would have to retain its hold on the laminates well above the maximum operating temperature of the tool. There are three categories of bonding that could be applied to this type of application.

Adhesive Bonding

Very few organic adhesives exist that can operate above 480^{0}F (250^{0}C) for any length of time. The few that can, generally consist of ceramic powder filled epoxy resins. For short periods it is possible to use these materials up-to the average working temperature of a die-cast tool, but certainly not above that. The second category of adhesives capable of operating at the specified temperatures are the inorganic adhesives, such as enamels and fluoro/sodium silicate cements.

Inorganic adhesives are, commonly, based on silicates or glass/enamel emulsions. Ground and hydrolysed silicates mix readily with water, under certain conditions, to form a paste. When applied to a metal surface, the water evaporates and leaves a layer of silicates deposited on the surface. If this solution is placed between two sheets of steel and the water evacuated, a tenacious bond is formed that can operate up to and beyond 1652^{0}F (900^{0}C).

A major concern is the incompatibility between the coefficients of thermal expansion of the adhesive and laminates. To achieve good bonding of steel with these types of high temperature adhesives, three conditions must be met:

- A minimum bond thickness
- The bond must be in compression
- An even heating and curing of the tool

Most enamels/ silicates work comfortably up-to 1022^{0}F (550^{0}C) after which softening occurs. This does not mean that the bond will fail suddenly but it does decrease as the temperature rises to and beyond 1652^{0}F (900^{0}C). The problem with silicas and enamels is that in compression their resistance to failure is high, but in tension it is not. On enamel coated steel utensils the mismatch in thermal expansion is used so that as the temperature increases the enamel is under a compressive load. The thinner the film that can be achieved the lesser this problem becomes, and this is so with laminate tooling

A potential limitation will be with the size of the tool. Enamel / silica bonding is normally used where the part to be bonded can be heated evenly so the adherent passes through it's glass transition for only a few seconds to achieve the bond before it cools. With a larger tool as in the case of some of the tools used for laminate tooling, it may take as long as an hour to get the whole tool up-to the glass transition temperature. Tests are to be carried out using Finite Element Analysis to look at the thermal equilibrium and the radiation absorption of a laminate stack.

Brazing and Soldering

Brazing and soldering are established processes for joining sheet metal. Some initial work with silver solders has proved successful in low temperature applications (below 450^{0}C) such as laminate injection mould tooling. Molten silver solder was poured onto, pre-heated, clamped laminates and, through capillary attraction, was drawn between the laminates. The major drawback with this approach was where no voids exist between the clamped laminates and therefore no material was drawn into this area.

An alternative is to use a thin sheet or foil of brazing material whose melting point is above that of the aluminium being forced into the laminate tool and less than the melting point of the sheet steel. Many such brazing foils exist that are as thin as 0.001mm thick and are commonly used in the Aerospace industry for bonding honeycomb structures. By placing foil between the laminates, the complete bonding of the laminates to each other is ensured. Establishing a suitable brazing process will be one of the main areas of research after the thermal fatigue tests are completed.

Solid Phase Welding

Solid phase welding removes the need for a secondary bonding material between the laminates. During bonding, the inter-layer boundaries of each laminate are excited to such a degree that the material at each boundary diffuses. On cooling, all the laminates are welded into one complete solid.

This approach offers the most practical solution to bonding as, on completion, there is no secondary material between the laminates that would suffer differential thermal expansion. The only drawback will be cost. There are many methods to produce a solid phase weld:

- Ultrasonic excitation
- High Frequency resistance welding
- Friction welding
- Explosive welding
- Diffusion Welding

In addition to the cost, each process is limited by the depth at which it can penetrate a laminate structure. In a large laminate tool it is unlikely that a large enough ultrasonic field, for example, could be generated to bond the laminates deep in the stack, and this applies to many of the above processes. Some encouraging work has already been done by Nakagawa[10] with diffusion welding of laminates and this work will be extended to moulding applications.

SECONDARY FINISHING OPERATIONS

Stair-stepping is a function of the slicing of the CAD representation and is more pronounced on curved surfaces and shallow angled planes. Vertical planes (0° to the cut angle) are not susceptible to this stepping, however it is these surfaces which are most affected by any misalignment of laminates when stacked for assembly. Both the stair stepping and the misalignment can be eradicated by surface finishing. Where tools are complex or include deep recesses it may not be possible or practical to hand finish internal surfaces.

One technique which can be applied to finishing is Electro-Discharge Machining (EDM), but complex electrodes can be costly with unacceptably long lead times. By rapid prototyping an electrode from common data its manufacture can be undertaken concurrently with the laminate cutting operation. EDM in the form of die sinking is used extensively for surface treatment or modification of tooling, it is also far easier to texture or profile a copper electrode than to work on tool steel.

A technique has been developed at the Centre, for the manufacture of EDM electrodes from Stereolithography (SL) models [12] (Arthur, Dickens & Cobb). Producing an EDM electrode from an SL part can be achieved using either a positive or negative approach. Soar, Arthur and Dickens[2] have shown that where straightforward finishing operations are required from the EDM electrode then the electrode is first produced as an SL part. This is then coated with a conductive paint and copper is electroplated onto its surface, this approach is referred to as a positive electrode. In the case of this tool, accuracy of finish was critical which necessitated the use of a negative electrode. The SL form is shown in Figure 6, prior to electro-forming.

Within the original CAD model of the tool the form is created as an SL part. It is into the form that conductive paint is first applied and then acid copper electro-formed into it for a period as long as 80 hours. This deposits a layer thickness of about 5 mm of copper, after which, the SL part is burnt away. This leaves a perfect replication of the internal detail of the tool and would be used to EDM the laminate tool to achieve the specified finish.

CONCLUSIONS AND FURTHER WORK

Within the field of pressure die-casting there is great interest in the potential for using laminate tooling as a means of producing dies for limited runs. Using a laminate tool not only allows the manufacturer to produce prototype parts using their existing machinery but also allows the effectiveness of the tool design to be tested.

The research has produced sample laminate tools for thermal fatigue testing, due to the exceptional heat and pressure that such tools would be subjected to. Because of these working conditions, problems that have had to be overcome include; the design of solid inserts, the selection of suitable sheet material, effective inter-laminar bonding and secondary finishing operations.

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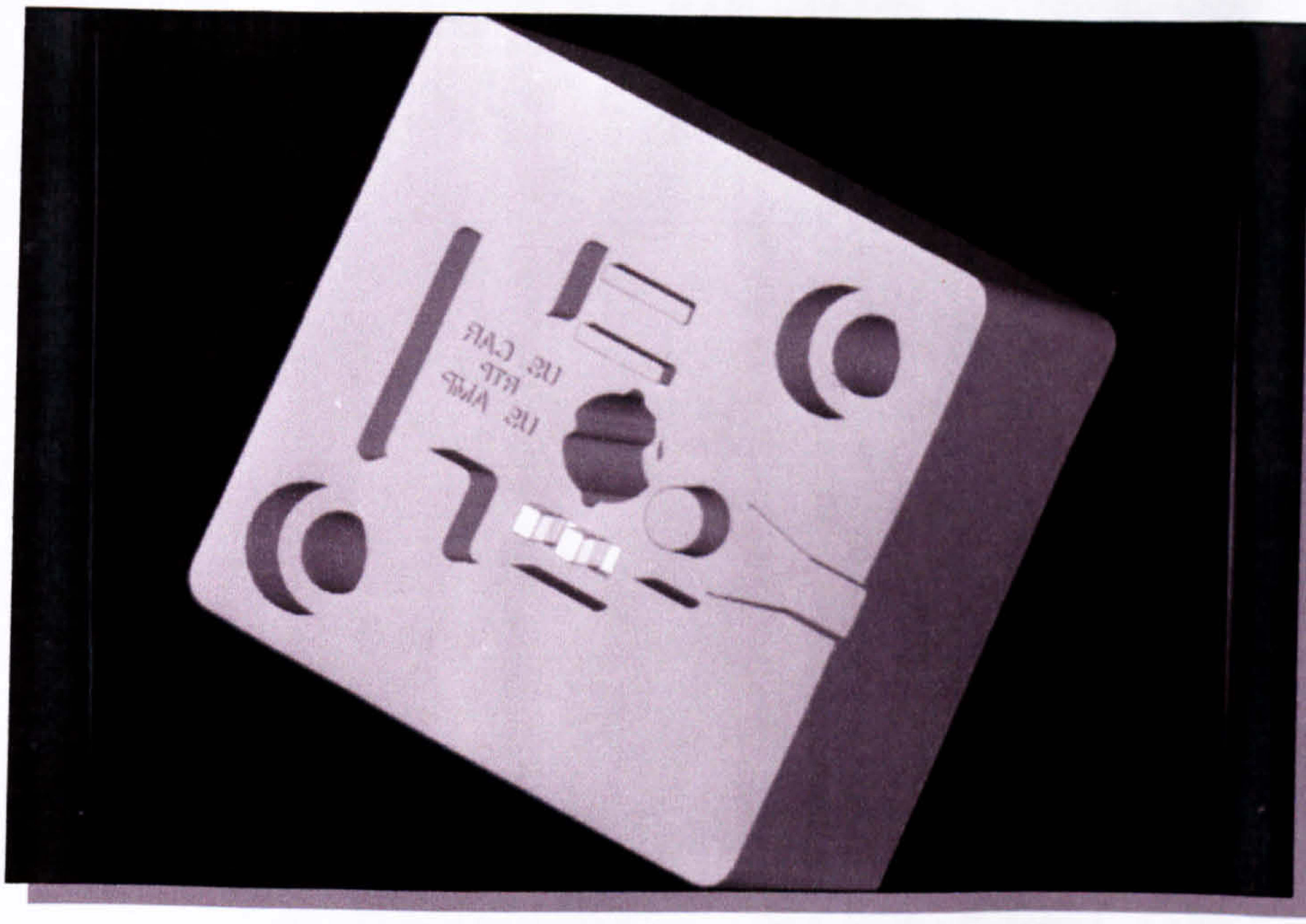


Figure 1. Solid CAD model of the USCAR die

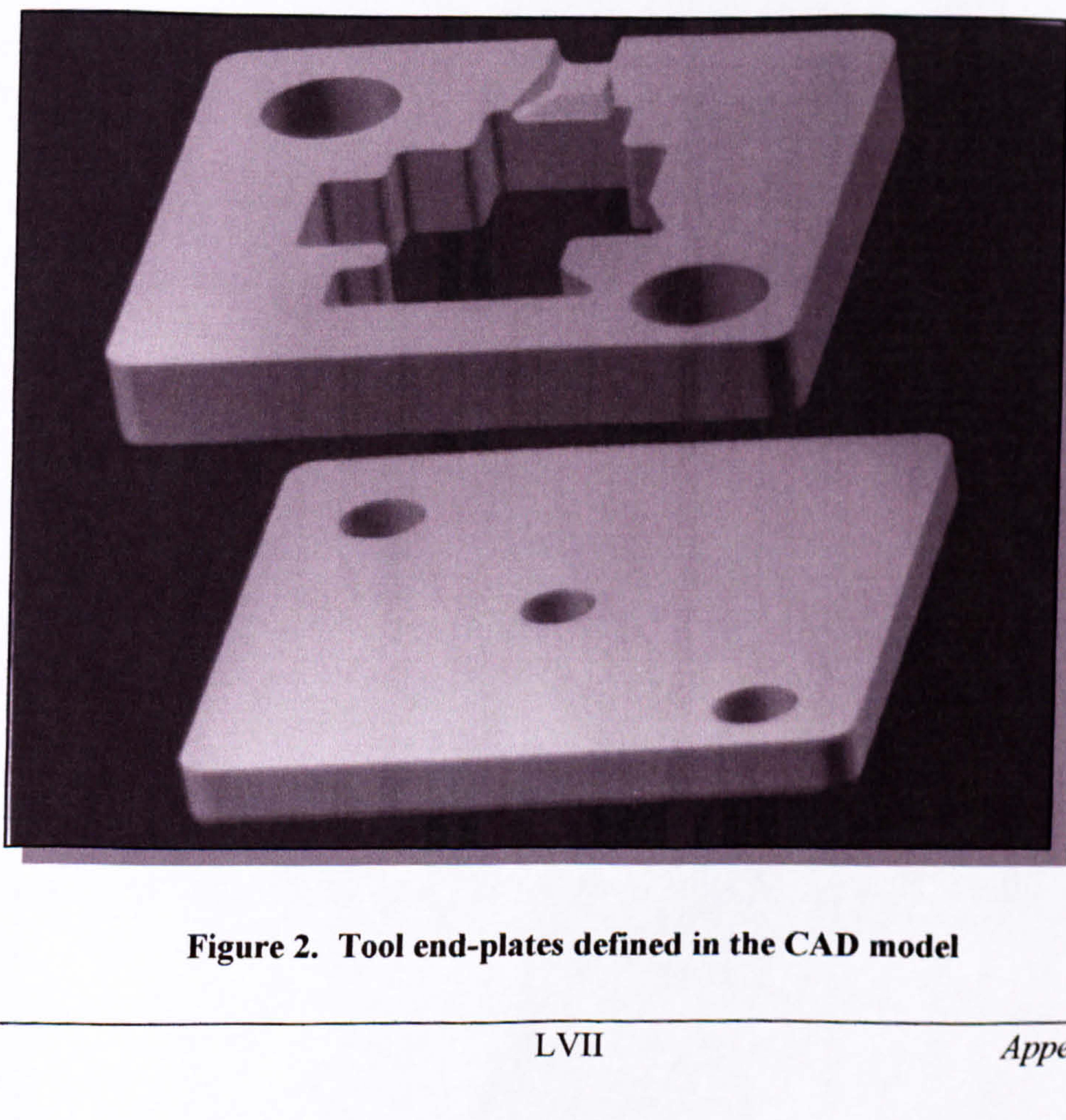


Figure 2. Tool end-plates defined in the CAD model

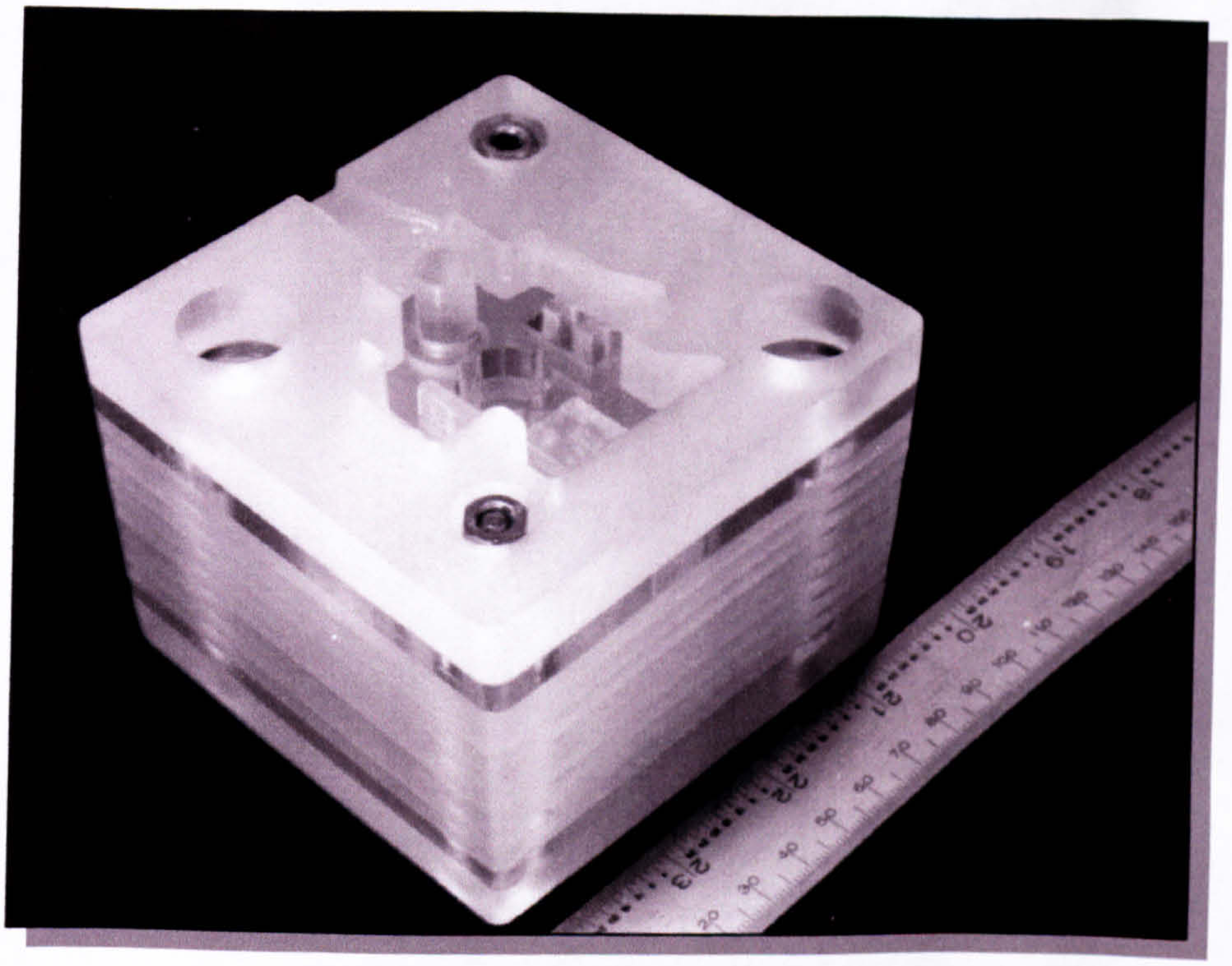


Figure 3. Solid insert created as SLA part

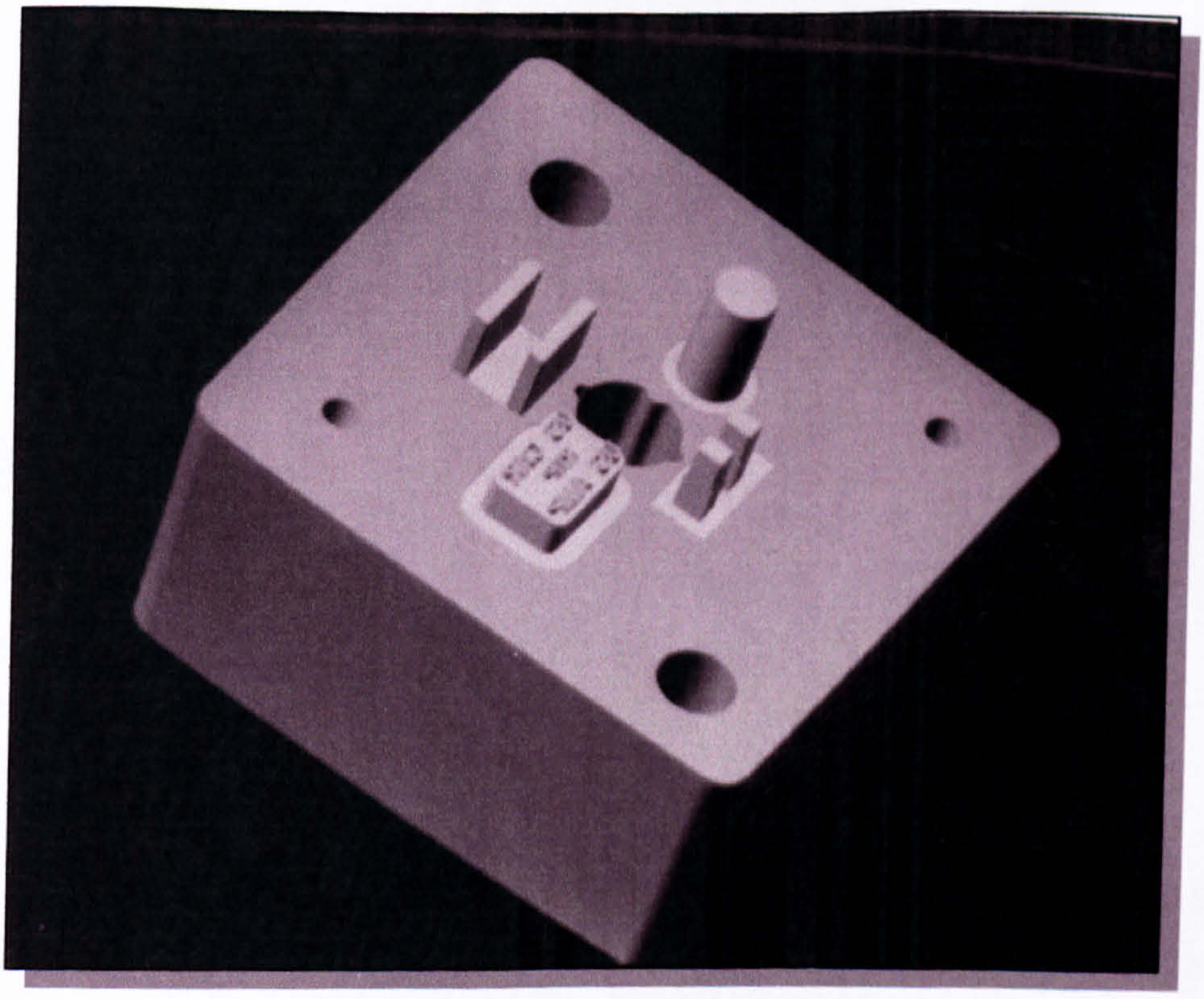


Figure 4. Sliced model excluding end-plates

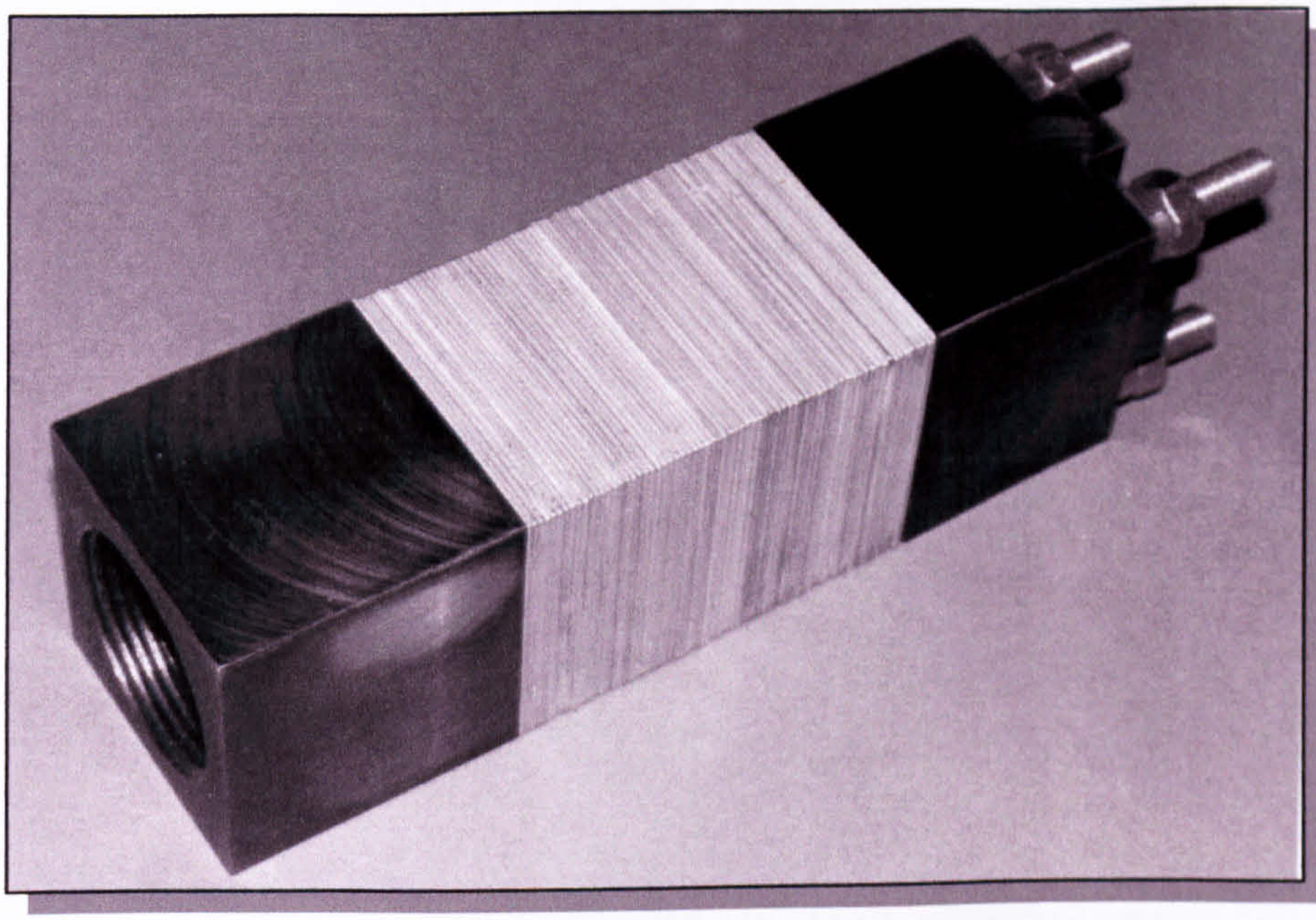


Figure 5. Laminate thermal fatigue test-piece

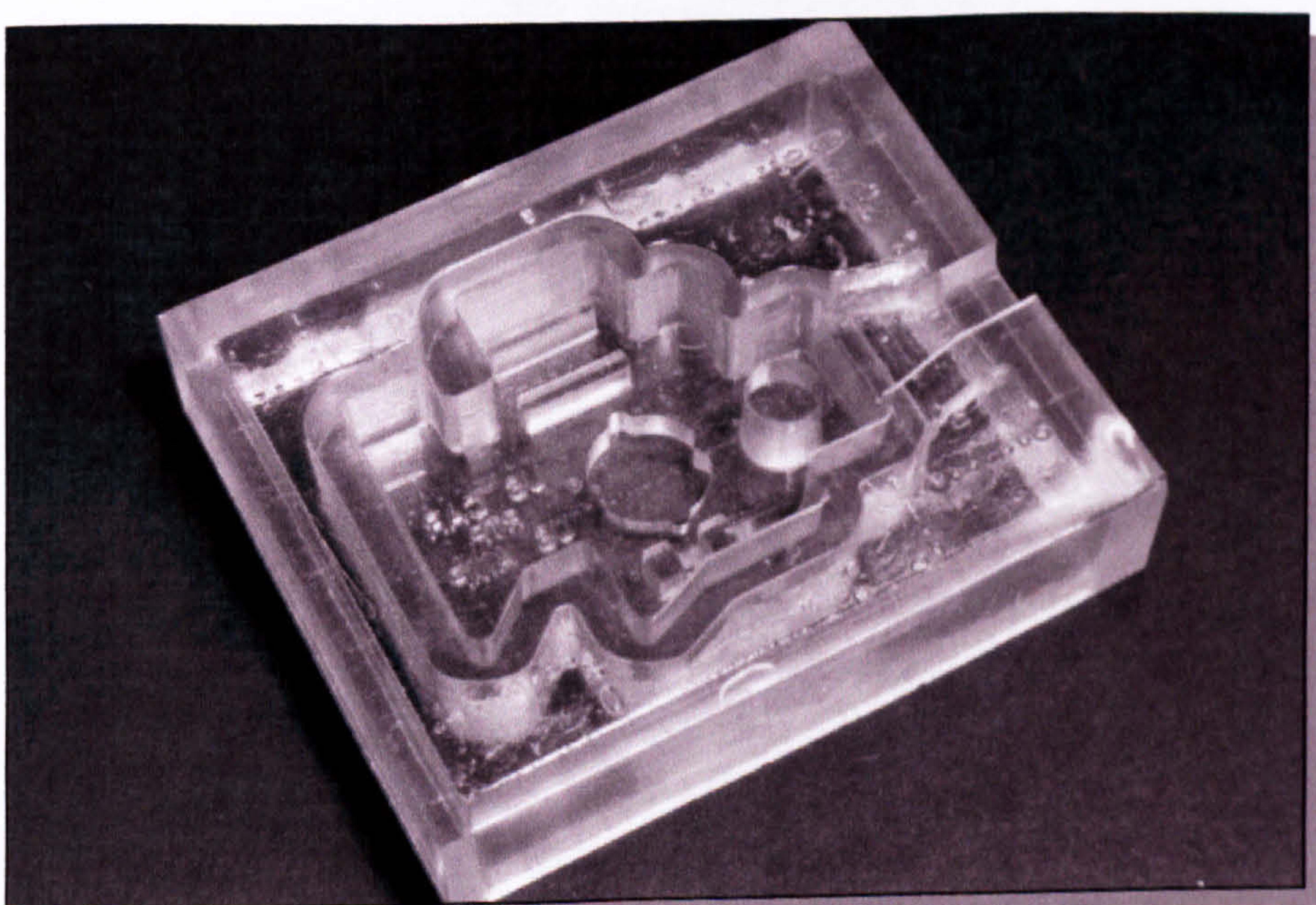


Figure 6. Negative SLA part prior to electro-forming

Deflection and the Prevention of Ingress within Laminate Tooling for Pressure Die-Casting

Soar R.C. and Dickens P.M.

Proceedings from: Solid Freeform Fabrication Symposium 1997, August 11-13 1997, The University of Texas at Austin, Texas, USA, pp307-317.

ABSTRACT

Within the context of Rapid Tooling, we are currently assessing the fundamental limitations of Laminate Tooling for pressure die-casting (PDC) applications. The use of individual laminates to form a die-cast tool presents it own problems, namely the prevention of excessive deflection that may lead to the ingress of pressurised molten aluminium between laminates. Ultimate solutions lie with bonding and clamping techniques of which work is already underway. This paper describes an initial study to establish the fundamental laminate die behaviour in extreme die-casting environments.

INTRODUCTION

Of all of the Rapid Tooling processes, Laminate Tooling is probably the simplest to conceptualise. The process uses the layered data from a 3D CAD model of a tool. Each slice is exported via DXF to a laser-profiling machine. Each of the DXF files defines one laminate of the tool and all are nested to fit a pre-defined sheet of steel, aluminium, stainless steel, etc. After cutting they are de-burred and assembled into the finished tool. The benefits of laminate tooling[1] can be summarised as follows:

- The production of large-scale tooling, as the size of each laminate is only restricted by the size of the laser profiling bed.
- The inclusion of conformal cooling channels for decreased cycle times.
- The replacement of damaged or worn laminates.
- The exchange of laminates for different profiles within a tool.
- Low cost and time of production, as there is little capital layout due to the abundance of laser sub-contractors.

Laminate Tooling is becoming attractive to die-casters because of the huge expense of conventional die production. e.g. dies commonly require modifications after manufacture and there is the problem of reducing 'hot-spots' within a die. Conventional die manufacturing may only allows for one attempt to get the design correct, the die must also be dedicated to producing many tens of thousands of parts to justify the cost. The rapid increase in the use of die-casting, particularly of aluminium to reduce fuel consumption and increase performance in cars, has resulted in larger dies, running faster. In addition, product lines can change annually requiring new tooling.

Laminate Tooling has the potential to offer low cost, large scale dies for limited runs. Even if they cannot perfectly match the performance of a conventional die they can allow the die-caster to produce prototype tools that can be run on the die-cast machines. This makes possible the following: the study of material flow throughout the die; the formation of hot spots and soldering (molten material bonds to the die); the effectiveness of cooling channels; ejector pin layouts; vortices; overflows; gating; etc. By exchanging laminates within the die many iterations can be carried out before the final die design is set.

Some of the groups involved in the development of Laminate Tooling around the world include: Stratoconception®[2], CIRTES (France); Nottingham[3], Warwick, Leeds & Liverpool Universities (UK); MIT[4], Clemson[5] & Ohio State[6] Universities (USA); DTI[7] (Denmark); Tokyo University[8] (Japan); most are backed by major automotive and aerospace sponsors keen to see a viable process.

LAMINATE TOOLS FOR PRESSURE DIE-CASTING

For the experimental work an EMB100 hot and cold chamber pressure die-casting machine was used. This is by no means the largest die-casting machine but it is fairly typical. Specifications in its cold chamber set up are shown in Table 1:

Die Locking Force	75 Tons (Imperial)	76 Tonnes(Metric)
Size of Moving Platen	16" by 16"	406 by 406 mm
Weight per Shot (Al)	.65 lbs	.29 kg
Volume per shot	6.5 ins^3	106 cm^3
Dia. Of Inj. Plunger	1.25"	31.8 mm
Total Force on Plunger	11,775 lbs	5,341 kg
Max. Pressure on Metal	9,600 lbs/in^2	674 MPa
Min. Cycle Time	4 secs	4 secs

Table 1. Specification of EMB 100 tonne die-casting machine

The casting material chosen was Al-Si8-Cu3 or LM24 (BS1490)/A380 (ASTM). This alloy is globally used as one of the most applicable to pressure die-casting. Cast aluminium is by far the largest sector in the PDC field[9]. However, it readily oxidises and is aggressive to steel dies. It also has the highest melting point at 750°C. If a laminate die can withstand the pressure die-casting of aluminium it will be suitable for zinc, magnesium as well as low pressure applications.

The research took four routes to achieve the aim of viable laminate tooling for pressure die-casting:

- Selection of suitable sheet material and thickness.
- Testing laminate stacks against failure through thermal cycling/stress.
- Assessing the fundamentals of laminate die behaviour to withstand deflection and ingress of molten aluminium.
- The bonding of laminates for extreme environments.

The first two sections have been covered in previous papers in conjunction with United States Committee for Automotive Research (USCAR)[10]. A recent paper, in conjunction with GEC Marconi Hirst Division[11], covers the last section. This paper asks the more fundamental question of whether inter-laminar bonding is required at all. Also, what design constraints exist for laminate dies and over what aspect ratio will individual laminates fail or distort

PROBLEMS OF LAMINATE DIES IN PDC ENVIRONMENTS

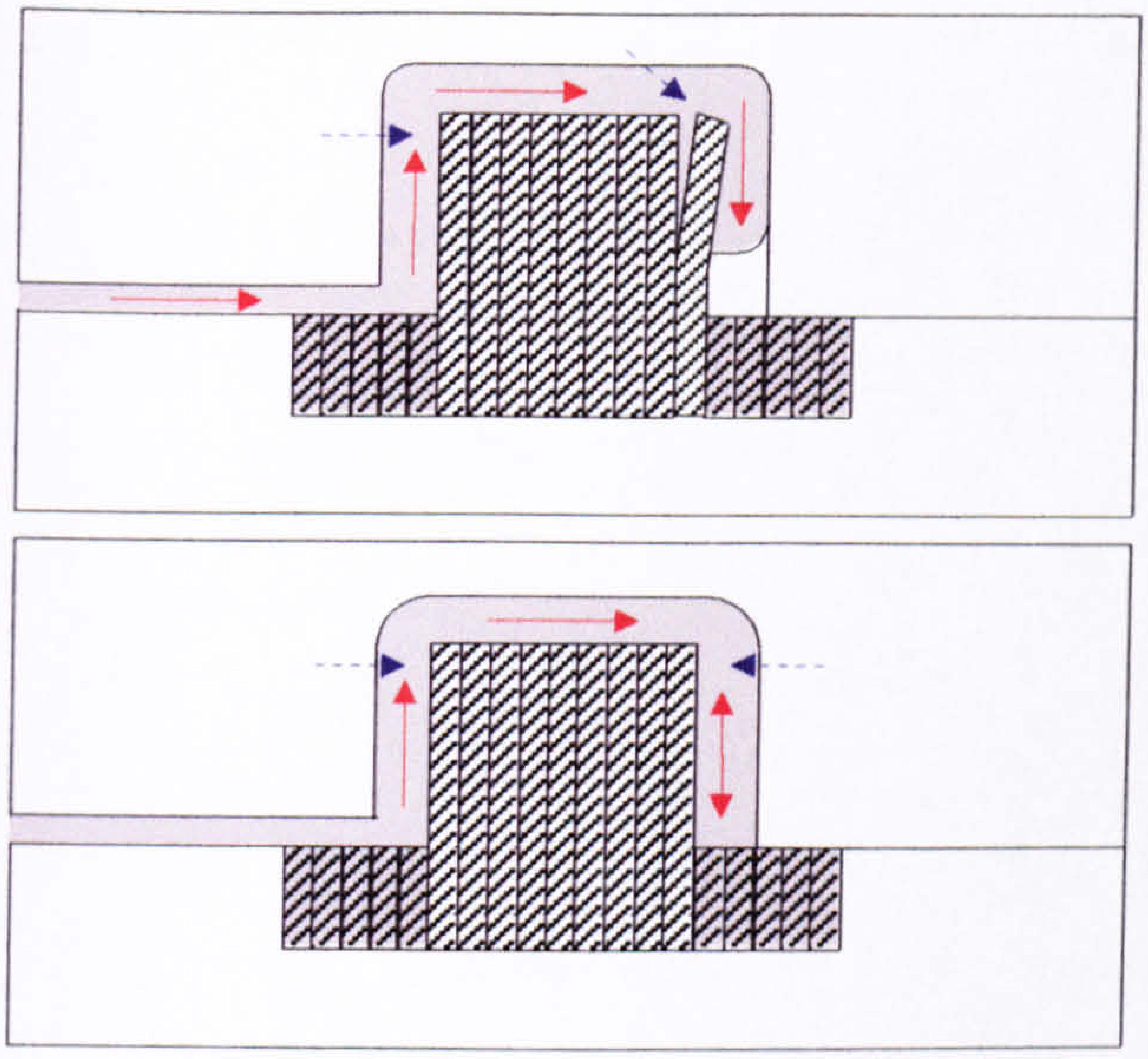
When using Laminate Tooling for pressure die-cast applications there is the possibility that molten material may force itself between the laminates of an up-stand feature within the die. If this occurs, then the subsequent casting may solidify onto a feature and be impossible to remove without damaging the tool.

For any laminate die design, the amount of deflection that occurs on an up-stand feature will be proportional to its height, area and geometry, as well as its orientation to the flow of the incoming material. Essentially, for any given sheet material there will be a design limit. The objective of this research is to find out, considering the unique conditions of die-casting, where this limit lies.

Due to the dynamic loading on the laminates, as molten material enters the die, the degree of deflection and the amount of ingress can only be established through direct observation of a laminate die in operation. What complicates matters further, is the nature of the molten material as it flows around an up-stand and fills the die. Depending on the influences of the various elements molten material will act as a dynamic load. It is not static, due to the brief time it takes to fill the cavity and the constantly changing pressure and velocity within the die. In effect, deflection will reach its maximum whilst material passes over the up-stand. However, it will cease as soon as the chamber is full producing an equal pressure on both sides of the up-stand. Four things could happen at this point and are illustrated in the Figure 1:

- Molten material could flow over the up-stand and the pressure could equalise on both sides before any significant deflection or ingress of material occurs.
- If ingress has occurred in the up-stand during material inlet, the chamber could remain hot enough to allow the equalising pressure to force that material out of the laminate up-stands.
- Any material that forces its way between the laminates could chill so quickly that it will solidify before the back pressure can force it out and so cause the part to freeze onto the ejector side of the die set.
- If the deflection is too great the laminate could deform plastically and could normalise into this new position

A final point to make about the possible outcomes relates to the viscosity/fluidity and wetability of the molten material. Even with a large deflection, ingress may not be possible due to the viscous nature of molten aluminium.



When molten material enters the chamber the end laminates will briefly deflect. Whether there is a permanent ingress of material depends on the equalising effect when the material fills the chamber.

As material fills the die chamber completely and the pressure equalises, the elasticity in the deflected laminate may allow it to spring back. If the material chills too fast whilst the laminate is deflected, the part will freeze onto the up-stand.

Figure 1. Effects of material flow within die cavity

SELECTING SUITABLE SHEET MATERIAL

There is generally considered to be only one type of steel that is suitable for aluminium pressure die-casting: This is H13 hot work tool steel (BH13 in the US).The selection and location of suitable sheet material for this experiment has been a central part of the work so far. One of the first decisions made was to establish a suitable thickness for the sheet material. The trade-off is between the degree of finish and detail required in the assembled laminate tool against the assembly time and availability of the material. The fastest way to build a laminate tool is to use very thick sheet material. But, as Figure 2 shows, if the sheets are too large then all the detail is lost and secondary finishing becomes 90% of the job. The other extreme means the laminates would resemble a metal foil, as in Figure 3. The detail would almost be perfect but hard steels do not come this thin and the tool would be difficult to assemble.

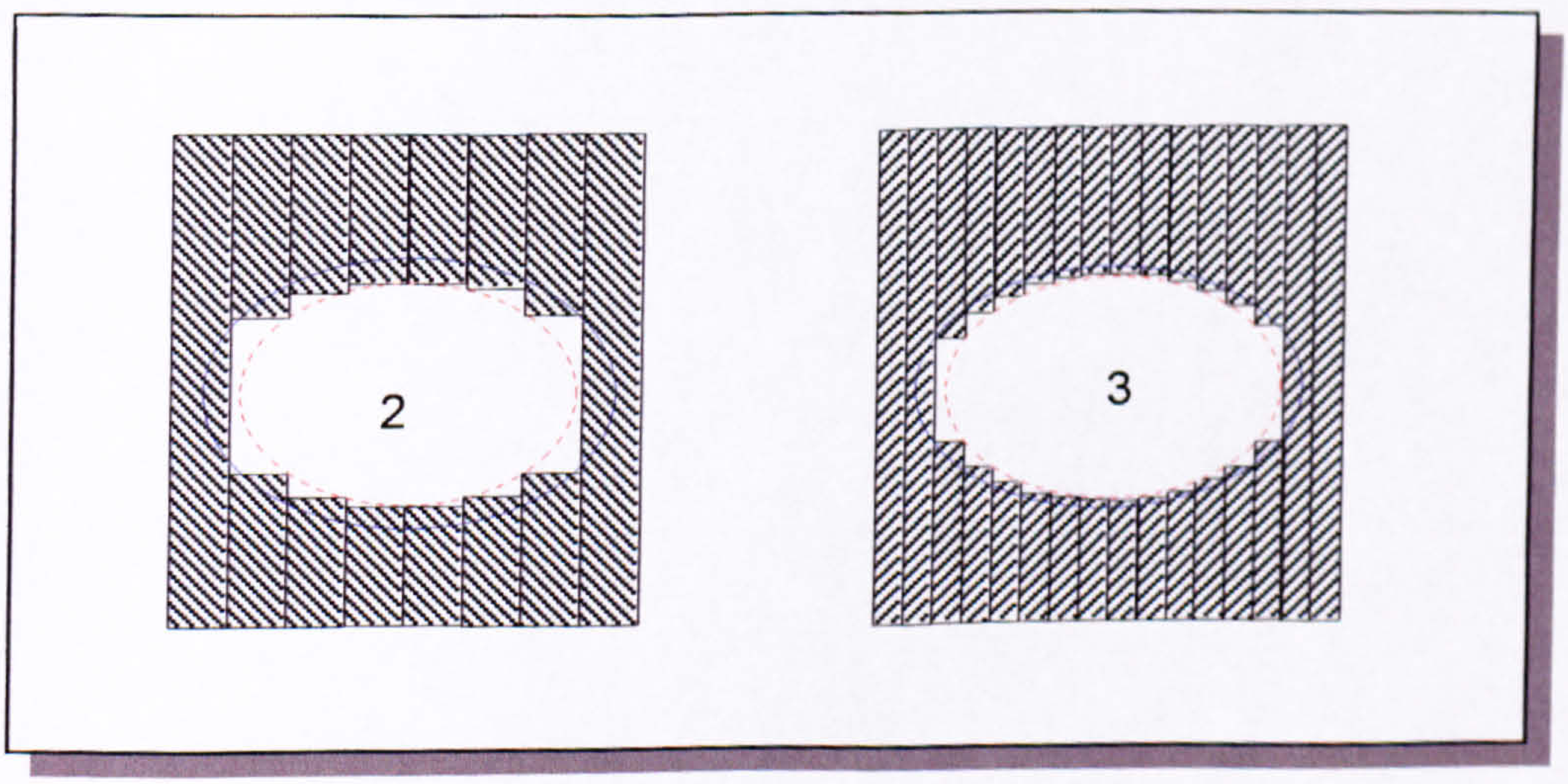


Figure 2 & 3. Effects of laminate thickness on steeping

The most readily available sheet thickness for high strength and thermally resistant steels, giving adequate detail, is one millimetre. One millimetre is the thinnest that most sheet materials can be purchased for high performance steels such as H13. Rolling steel this thin can improve the grain structure and alloy distribution, but it does set up stresses that must be relieved later on (this is done during final hardening and tempering).

THE LAMINATE TEST-DIE

The ultimate test die design consists of a number of isolated laminate up-stands. Each up-stand has a different aspect that will present one laminate in each group to receive the full force of the incoming, pressurised, molten aluminium. At a certain height there will be enough force to deflect this laminate to cause an ingress of molten material between itself and the laminate it abutts. Figure 4 shows a cross section of the two extremes of the up-stand arrays that will be created in the test die.

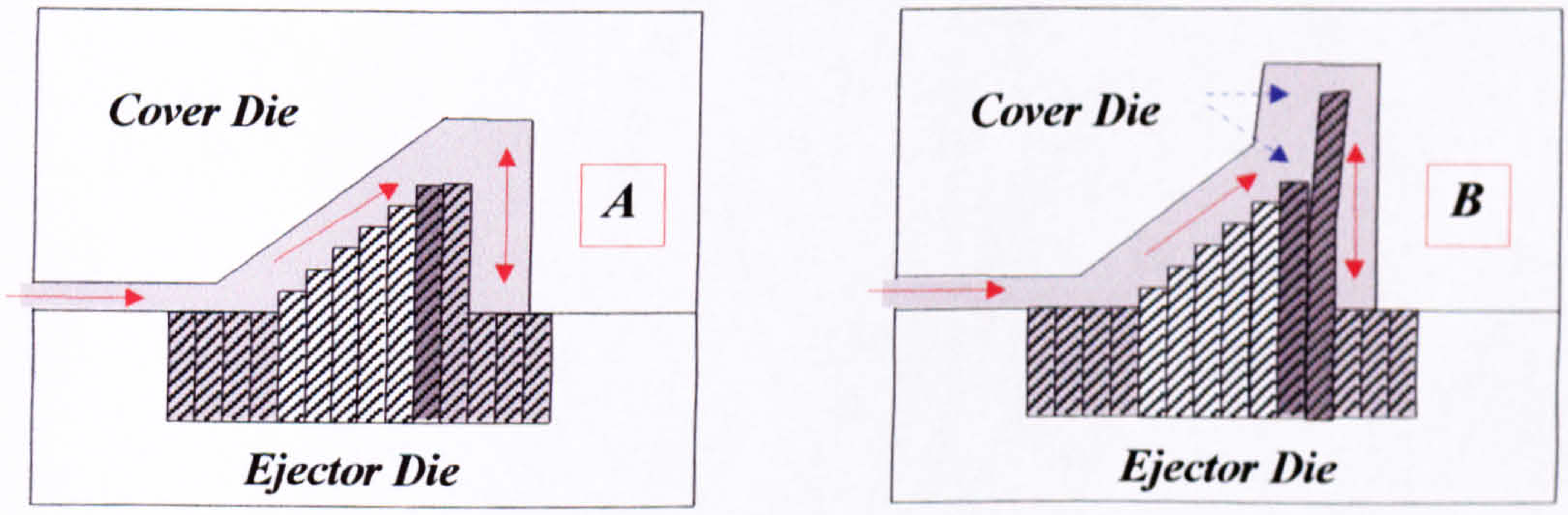


Figure 4. Effects of deflection on laminate up-stands

The simplified illustration *(A)* shows molten material entering from the left and being forced upwards at 45^0 over a ramp formed by the laminates. Each laminate stands 1 mm higher than the laminate on the left. This design will not incur any deflection as the laminates in the up-stand support each other and the end laminate does not protrude into the flow of molten metal.

On illustration *(B)* material enters from the left and is directed up the laminate ramp where it will strike the last laminate before passing over and around it. This laminate will deflect but may move to the upright position again, due to its elasticity/rigidity, before the cast freezes. Trying to measure this deflection as it occurs in the die would be impossible, this measurement can only be taken by examining the casting after removal from the die. The answer to measuring deflection lies in the second laminate positioned next to the tallest up-stand. If the last laminate deflects enough then there will be an ingress of aluminium that will freeze between the laminates. When the cast is removed from the die a 'witness mark' will remain that can be measured as a direct indication of the amount of deflection that occurred in the last laminate, as shown in Figure 5.

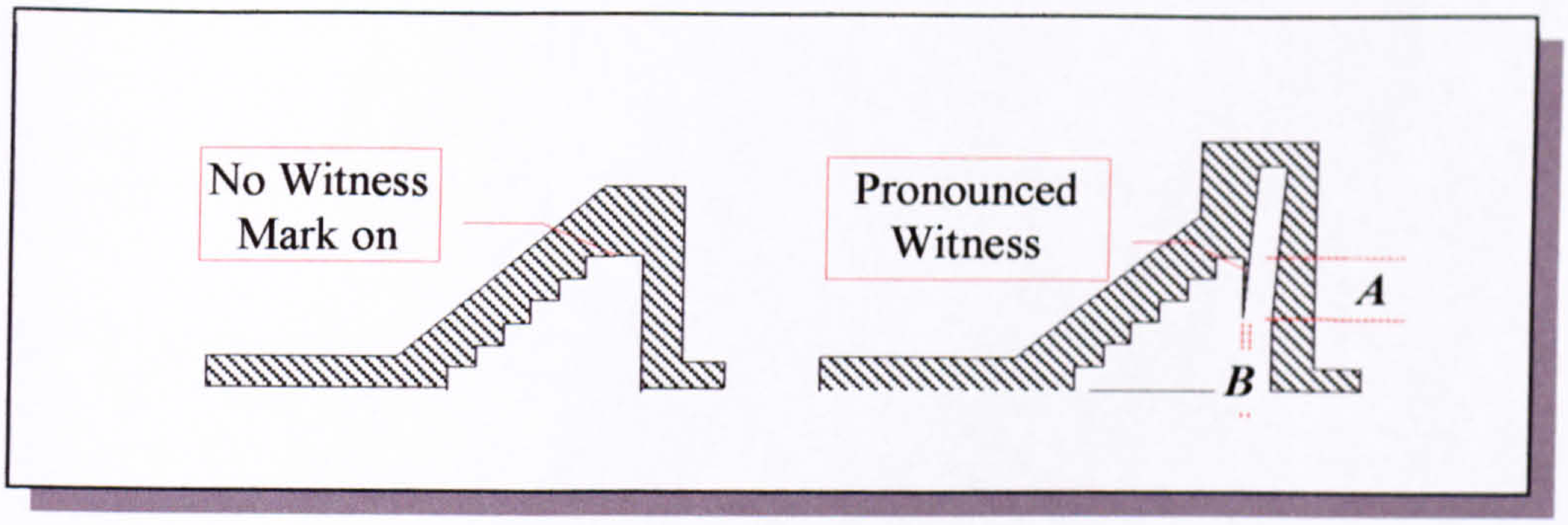
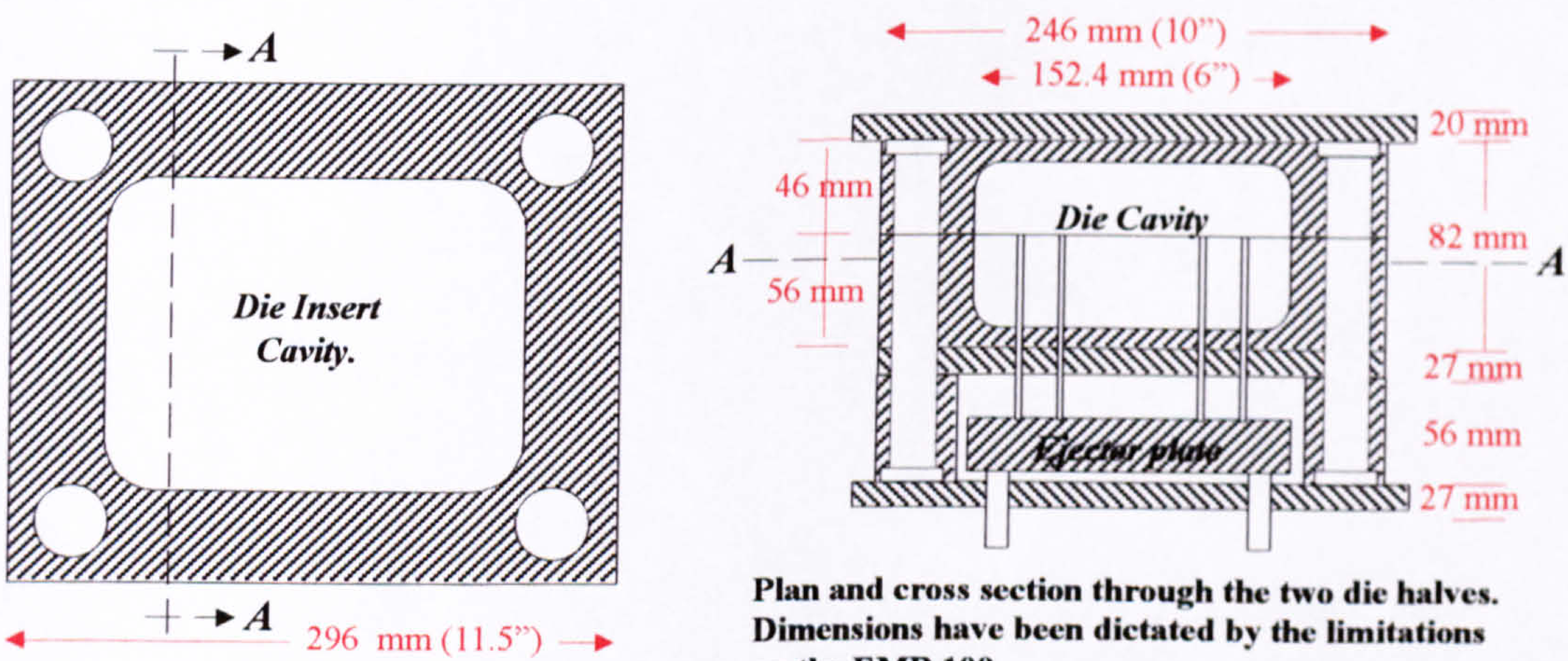


Figure 5. Measurable Witness Marks

Figures 6, 7 and 8 show the plan and cross-sectional view of the two halves of the laminate die. The laminate test die will be clamped into a bolster. The dimensions are shown in Figure 9:



Plan and cross section through the two die halves. Dimensions have been dictated by the limitations on the EMB 100.

Figure 9. Complete die assembly

The end-plates will be constructed in H13 to spread the clamping load on the individual laminates and prevent them from warping. Previous testing with GEC and USCAR has shown that a pressure of at least 10 MPa is necessary on each laminate to ensure rigidity and the elimination of any gaps between laminates this pressure will be provided by the eight M10 bolts.

The tool will run for around 500 shots as there is a time constraint on the use of the EMB100 die-casting machine. Over this time tool wear will be monitored as an indication of potential prototype life.

DISCUSSION

This tool is now currently in testing and the results will be published early in 1998. The results from this work will dictate where the research will move next. If ingress occurs too readily then the next stage will be to investigate suitable bonding techniques to overcome ingress in these applications. If ingress does not occur readily, then un-bonded laminate dies will be explored further. To produce a laminate tool with no inter-laminar bonding for pressure die-casting would be a huge cost saving over having to use some bonding medium. Instead of looking into bonding techniques, the research would move onto look at clamping techniques.

The data collected from this experiment will then be used to formulate a model that will allow the designer of a laminate tool to know the limitations of this process when applied to pressure die-casting. The model will be able to compensate for different die-cast machines, different grades and thicknesses of sheet steel and different materials.

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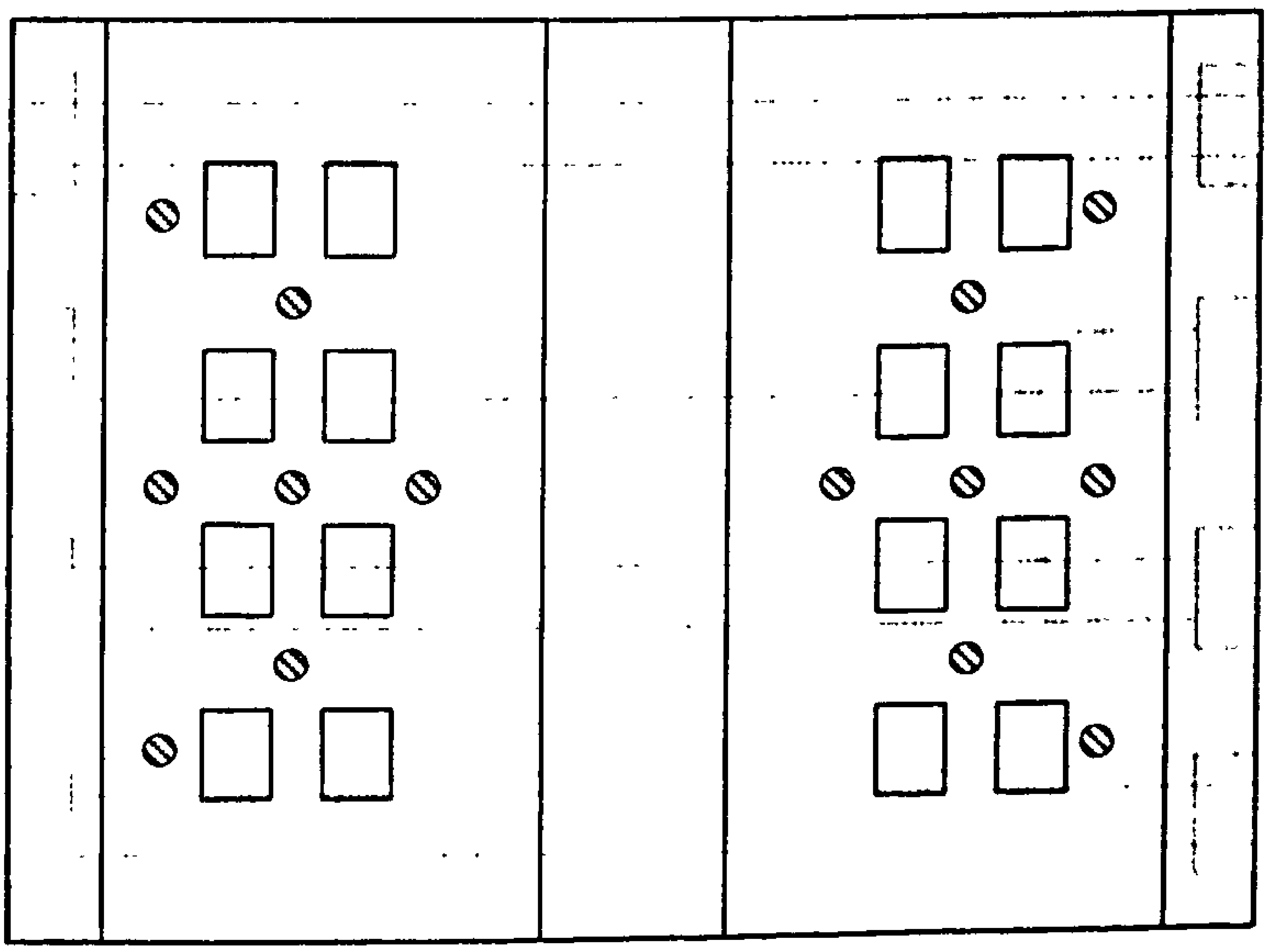


Figure 6.

Plan view of the ejector die, showing the laminate arrays. Phantom lines denote the M10 bolts used to clamp the laminates and prevent movement. End-plates and a central clamping plate are shown to allow the interchange of laminates to change the profile.

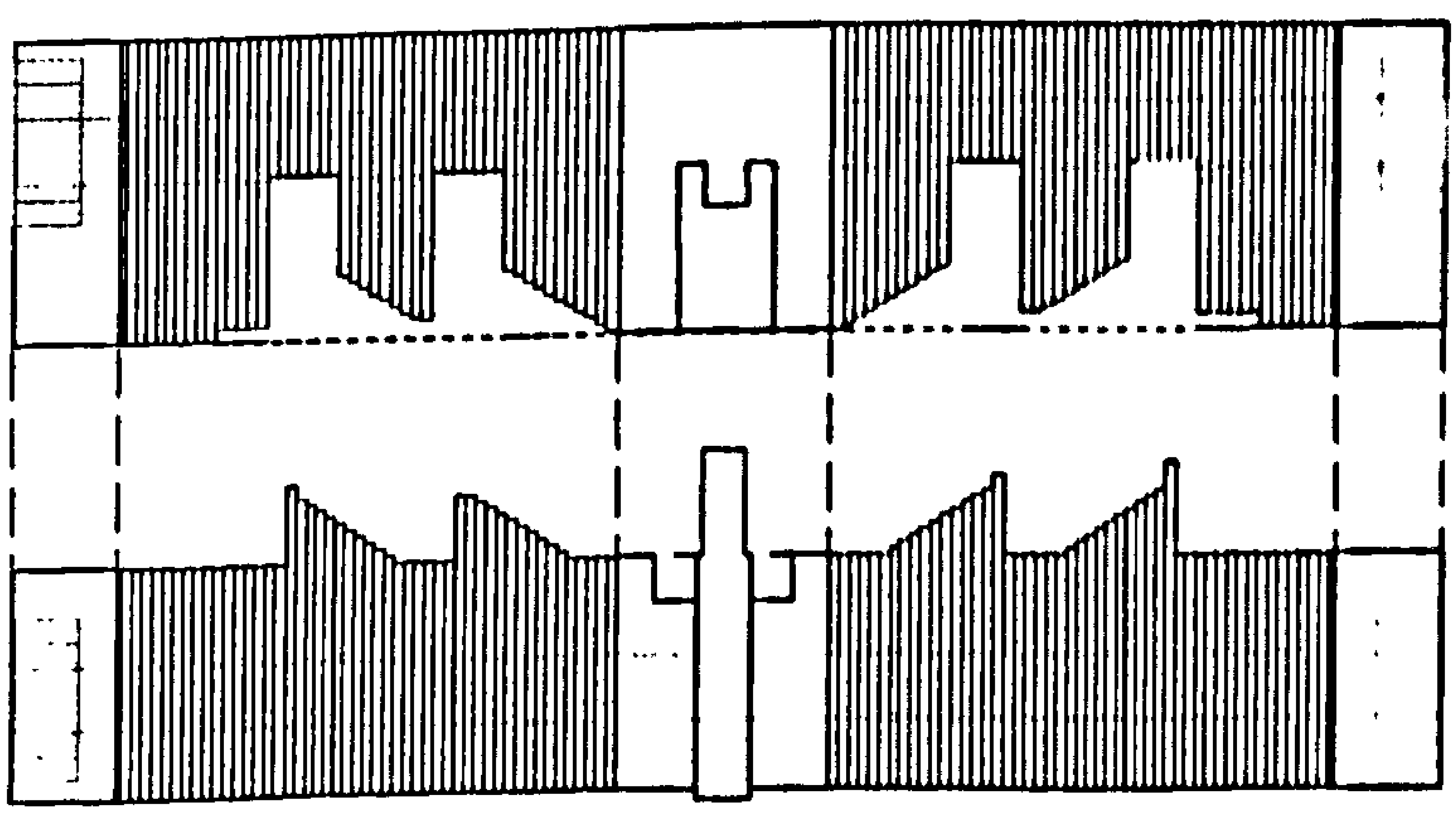


Figure 7.

Cross-sectional view of the cover & ejector die, showing the laminate arrays. Ejector pins are not shown but appear in Figure 8.

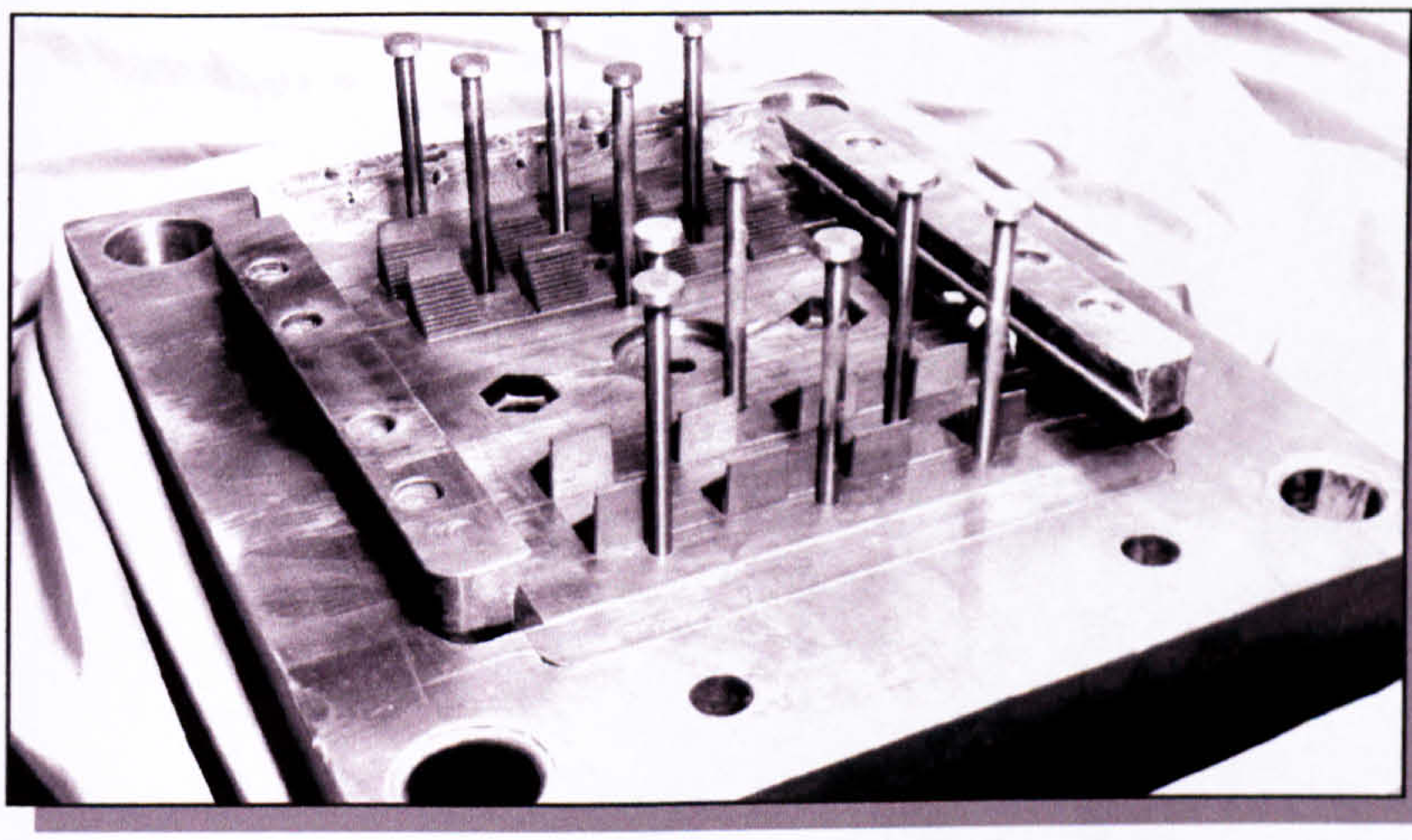
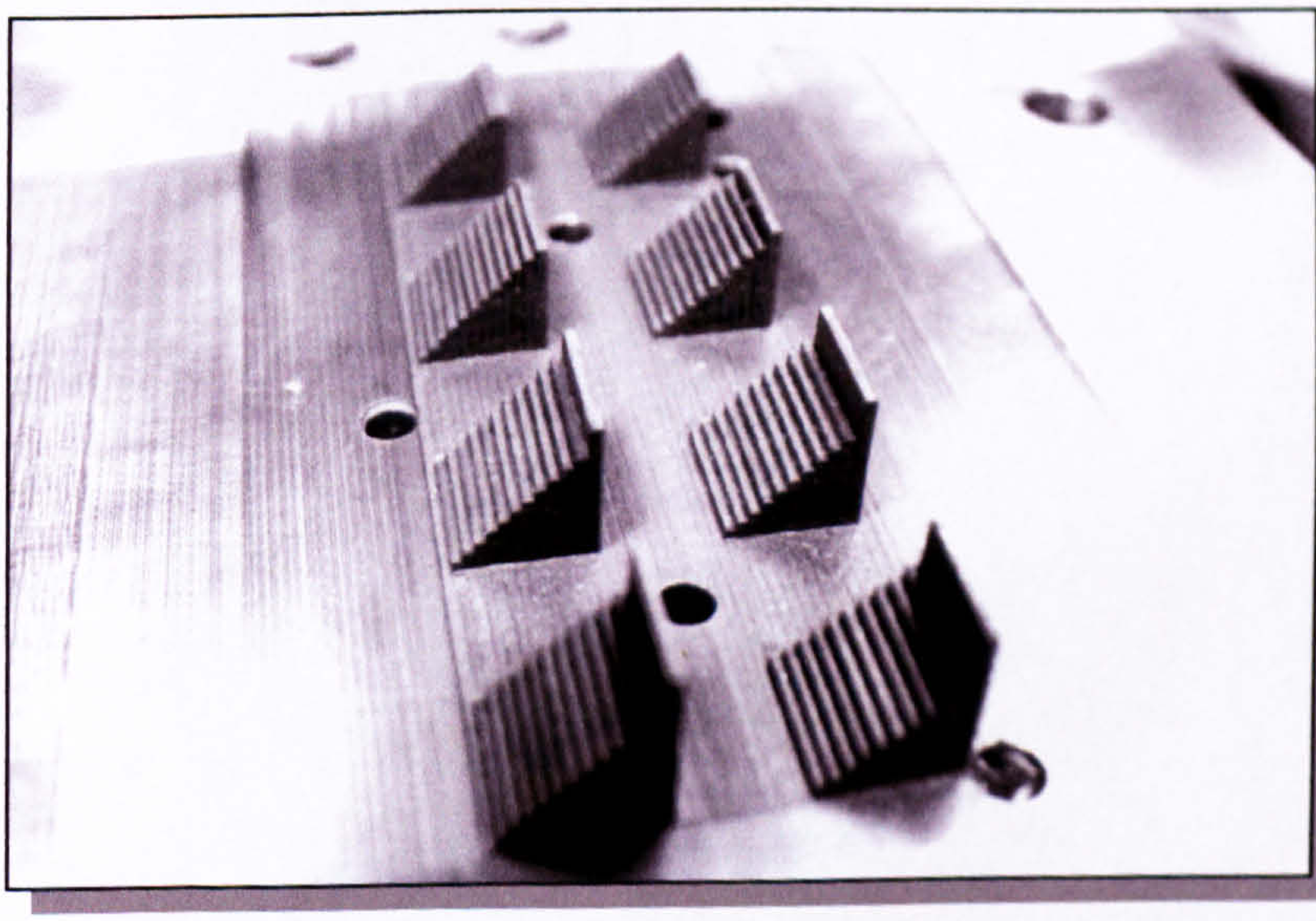


Figure 8.

Completed ejector die showing wedges used to hold the laminate die in the bolster. Ejector pins have been removed.

Figure 10

Two of the four rows of laminate arrays showing the laminate up-stand that will receive the full force of incoming molten aluminium to measure deflection.



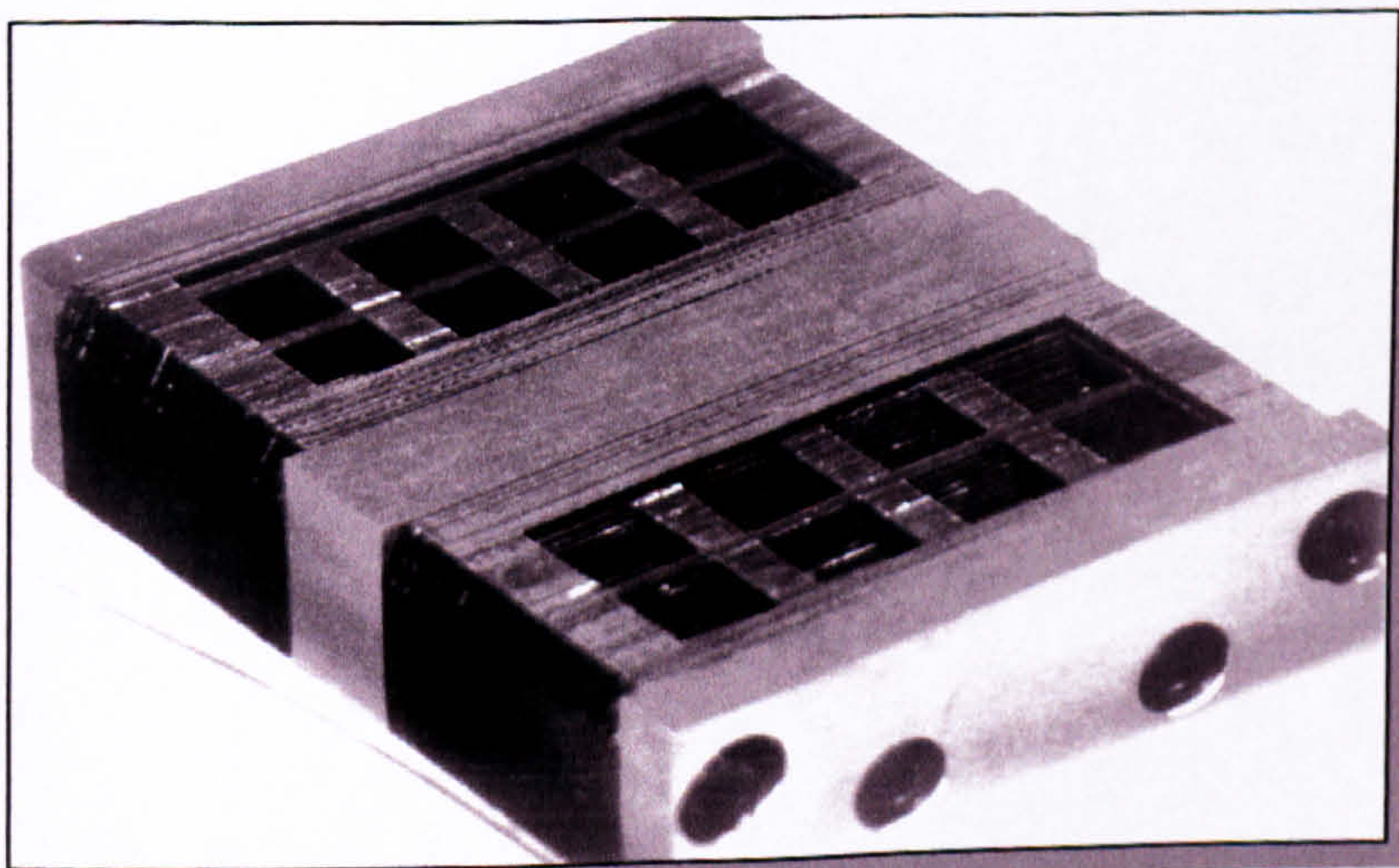
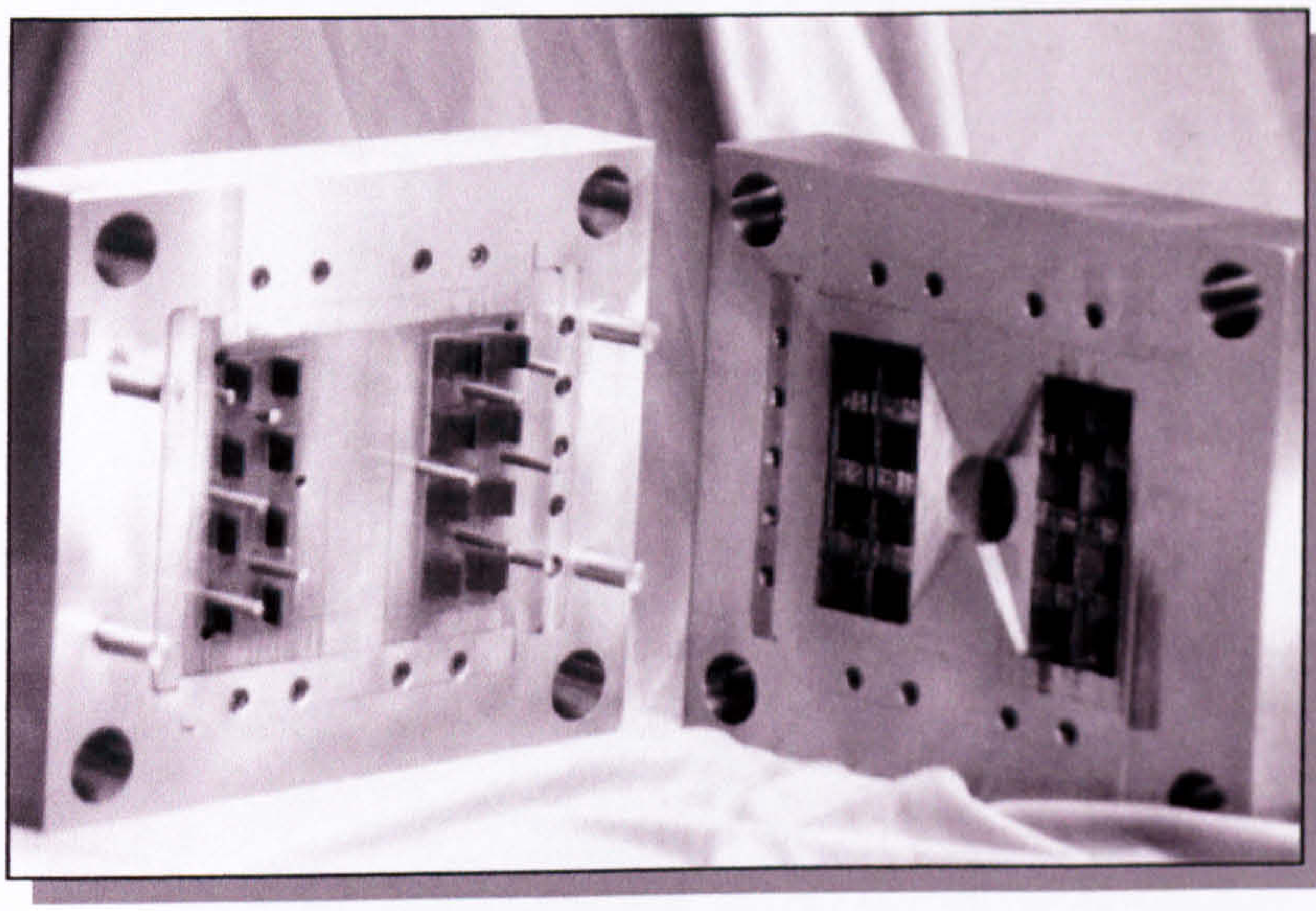


Figure 11

Laminates that make up the Cover Die assembled and clamped using solid end plates and a solid central core to facilitate disassembly.

Figure 12

The completed laminate test-die showing ejector pins and the fan gate in the cover die. The ground parting line makes the laminates hard to distinguish.



The Production of Large Rapid Prototype Tools Using Layer Manufacturing Technology

Bocking C., Jacobson D.M., Sangha S.P.S., Dickens P.M. and Soar R.

The GEC Journal of Technology (formerly the GEC Journal of Research), Volume 14, Number 2, 1997, pp110-115.

Abstract

Most of the techniques used to translate CAD into part manufacture are limited for size and in the materials they can use. Thus, for example, the widely used technique of stereolithography can generate only relatively small objects and in only photopolymer. Further processing is required to translate these models into metal parts. Here, a novel approach to Rapid Tooling is described in which objects can be produced directly in a wide range of metals in which layers of the requisite metal are diffusion-soldered or brazed together. This approach, called Metal Layer Object Manufacturing (MELOM), is flexible with regard to part size and is capable of creating tools for demanding use, including pressure die-casting.

INTRODUCTION

Rapid Prototyping and Tooling processes [1] are now becoming more widely accepted as part of the new product development cycle. Rapid prototype models can be produced using several methods, including stereolithography (SL)[2], selective laser sintering (SLS) [3], layered object manufacturing (LOM)[4] and solid ground curing (SGC)[5]. The materials that can be used for these models are often limited to polymers although certain ceramic and metal models can now be fabricated. Many techniques exist for the production of tools from prototype models and these include investment casting [6], metal spraying [7], vacuum casting [8], electrical discharge machining (EDM)[9] and many more [10]. However, the maximum size of the models that can be produced is limited to that of the working volume of the model fabrication equipment. It is possible to join models together to form a larger structure for subsequent tooling operations. The maximum working area of SL equipment is currently of the order of 500mmX500mm. One disadvantage of large models produced by these methods is that dimensional errors tend to increase with increasing size.

These Rapid Tooling methods are limited in the final materials of construction as well as the maximum size and so are generally unsuitable for large size tooling of injection mould cavities. In addition, the models or tools produced by secondary processes are unsuitable for metal die-casting moulds because of the high temperatures encountered. The production of such large tools - either as prototypes or as production tools by conventional methods is extremely expensive and time consuming. In order to produce large tools of this type directly in metal, a new approach is required.

One of the methods mentioned above, LOM, builds up the model using layers of polymer coated paper, as shown schematically in Figure 1. The first layer is fed from a continuous sheet onto a support bed and the outline of the layer is cut using a CO_2 laser. The unused paper is fed onto a take-up spool and in so doing presents the next layer onto the first on the support bed. A hot roller is applied to bond this second layer to the first. The second layer is presented and its outline cut. The process is repeated until the complete model is formed. Various feedback systems are employed to ensure that the model height and layer profiles remain in correct alignment. The process described here is similar in its approach to LOM. However, metal sheet is used instead of paper and the process may not make use of a continuous metal sheet but, rather, single sheets. As there is no limitation in the size of the metal sheet used, very large layer profiles may be cut to build up substantial tools. The problem to date was that it has not been easy to bond the metal layers together in a controlled fashion. However, this objective has now been achieved, as described below.

A few large tools have been produced at the University of Nottingham by a system of layered object manufacture using steel sheet. The tool is made up from layers of sheet steel that have been laser-cut under computer control to provide the profile required of the final tool. One inevitable result of using LOM methods is that the cavity profile has a noticeable 'staircase' effect resulting from the offset of each sequential layer, whenever the profile of the object is not vertical, and is a function of the layer thickness. However, for Prototype Tooling, this is not considered to be a major handicap, although this effect may be removed by a finishing operation such as EDM or conventional machining. The layers were bolted together and the tools assembled in this manner were used for low-pressure injection moulding. Such tools, whilst acceptable for low pressure applications, were not suitable for higher pressure use because the layers were not bonded and sealed. This paper describes work carried out on a new method of Metal Layer Object Manufacture (MELOM) tool manufacture in which the individual layers are bonded together using diffusion soldering.

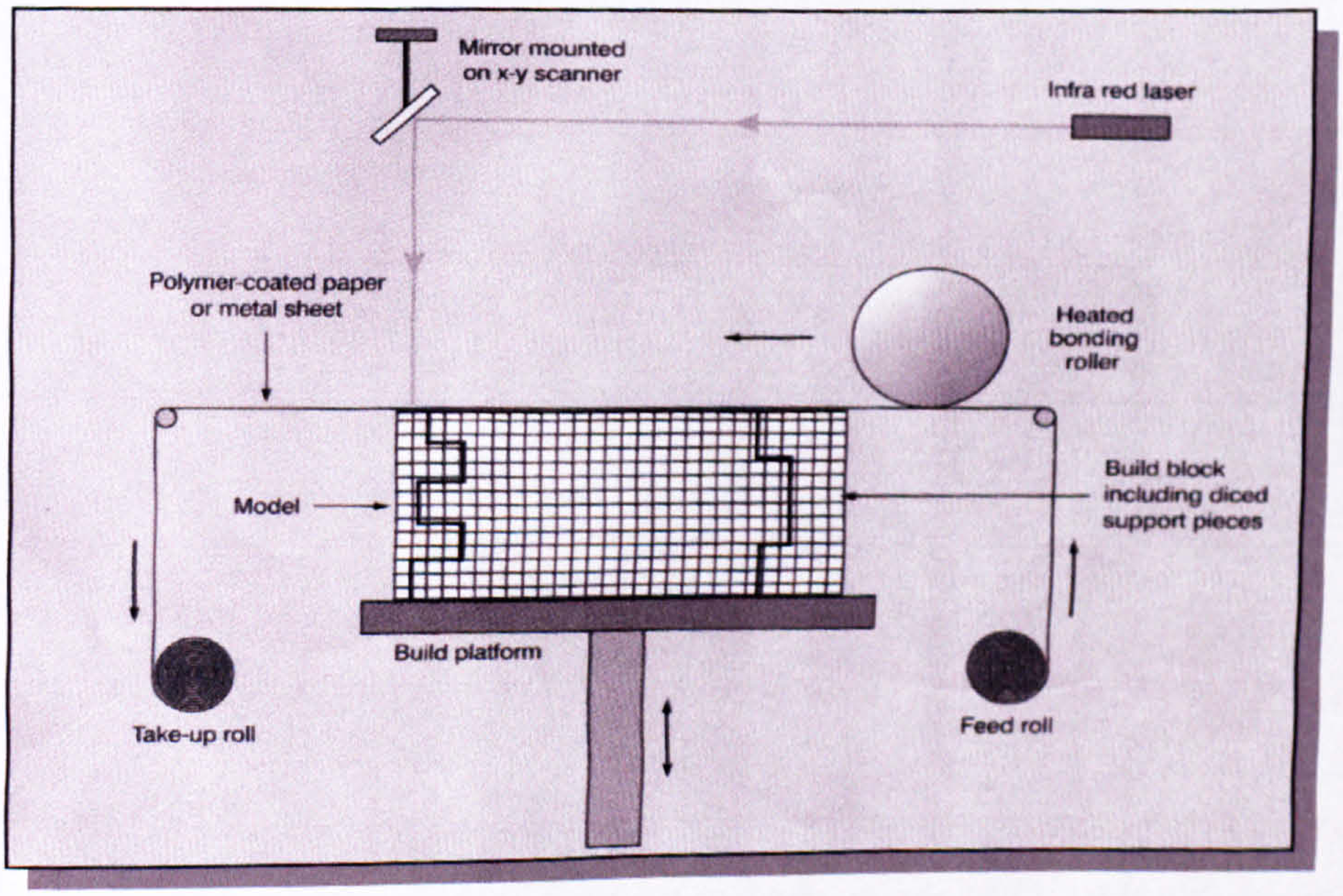


Figure 1. Schematic of conventional layer object manufacture (LOM) machine

Small-scale trials have been carried out using this MELOM approach to produce a fatigue test tool for the USCAR Group. USCAR, which is funded by General Motors, Ford and Chrysler, have an interest in low-cost, large-size, prototype tooling for the development cycle of new motor vehicles. This prototype was required to test the feasibility of the technique for use as a water-cooled aluminium die-cast tool.

THE DIFFUSION SOLDERING PROCESSES

Before describing the fabrication of the prototype tool further, a brief account is given of the unique diffusion soldering process. Diffusion soldering may be described as a hybrid of soldering and diffusion bonding and combines the benefits of both types of joining process [11]. It combines the ability to fill joints that are not perfectly smooth or flat, which is a characteristic of conventional soldering, whilst enabling the assembly to be used at temperatures above the joining temperature, which is achievable with diffusion bonding.

Like soldering, the joining medium is a low melting point metal that will fill joints even when the mating surfaces are rough and irregular. On the other hand, the amount of solder in the joint is sufficiently restricted that, over the duration of the process cycle, the filler alloys with the material on the surface of the components to form new phases and thereby raises the remelt temperature of the joint. The slight amount of filler needed ensures negligible spillage of the molten alloy from the edges of the joint, ensuring that the latter remain crisply defined and undistorted. Although pressure needs to be applied during the joining operation, this is an order of magnitude less than that required for conventional solid-state diffusion bonding process and is typically no more than 5 MPa, The application of pressure ensures exceptionally good joint filling over large areas.

Diffusion soldering processes have been developed at GEC-Marconi Materials Technology Ltd, based on copper, silver and gold, combined with tin as the solder [12,13]. Where the parent materials are none of these metals, the relevant metals can be applied as coatings; this is because the depth of interaction with the filler metal can be tightly controlled by limiting the quantity of the solder metal that is applied as a capping layer.

In general, the layer of the base material (copper, silver or gold) needs to be sufficiently thick in relation to the layer of solder - here tin - that, following an appropriate heating excursion, the solder melts. It then reacts with the base metal to form a solid solution in the latter, following solidification, which will occur at the joining temperature.

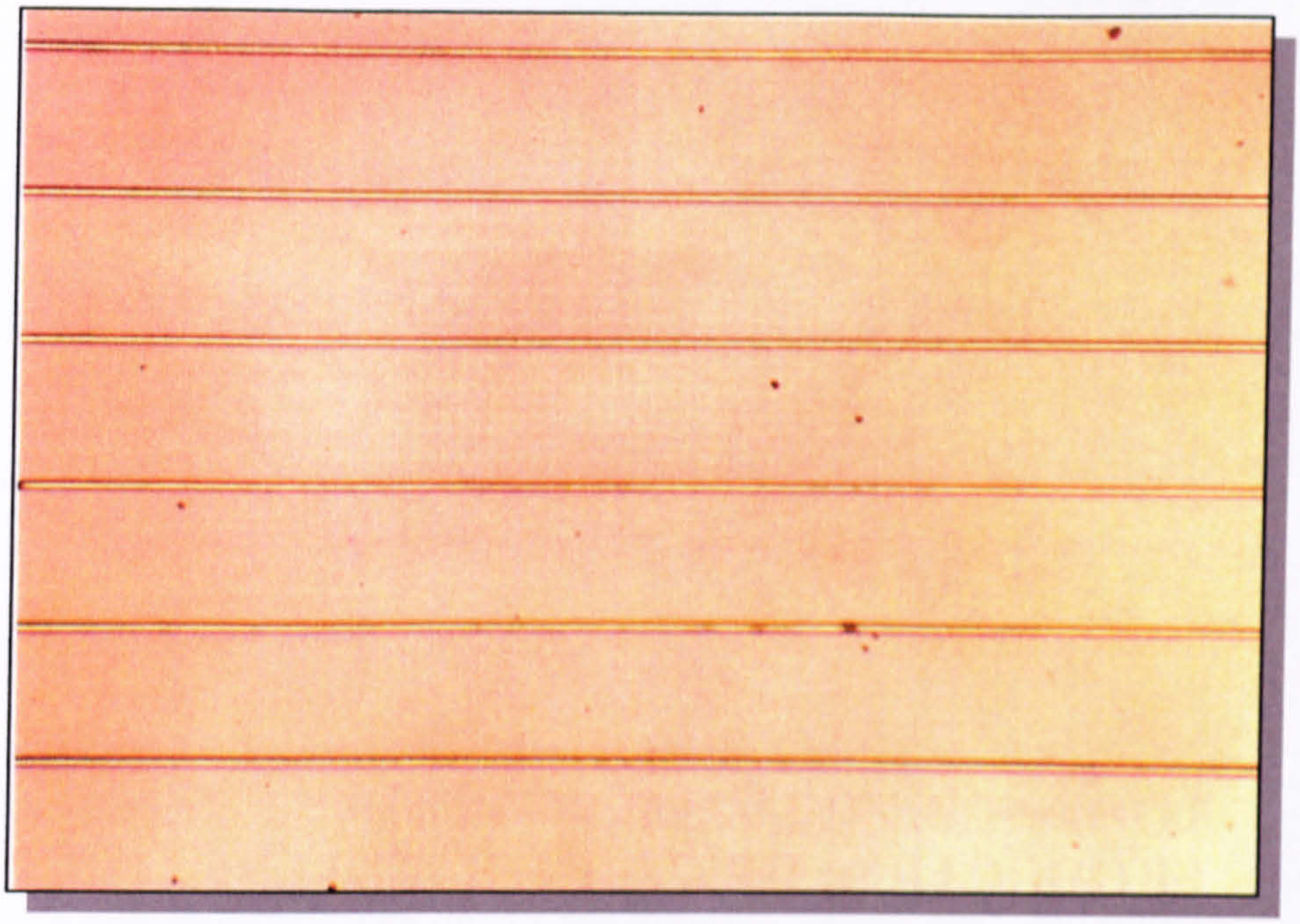


Fig.3. Multiple joints produced using diffusion soldering (X50)

The minimum temperatures required to achieve this result are shown in Table 1, for the three alloy systems:

Base Metal	Solder	Minimum temperature required to decompose intermetallic compound (^0C)	Relevant intermetallic compound
Copper	Tin	676	Cu_3Sn
Silver	Tin	480	Ag_3Sn
Gold	Tin	419	AuSn

Table 1. Minimum temperatures required to de-stabilise selected tin intermetallics with copper, silver and gold

These temperatures are defined as those above, in which the stable intermetallic compounds that intervene between the solder and the base metal decompose. In the case of the silver-tin system, the reaction will go to completion even below the decomposition temperature of the AG_3Sn compound, but the reaction kinetics will be significantly slower.

Strictly speaking, the term diffusion soldering should be used only for filler joining processes below 450^{O}C; above that temperature the process enters the domain of brazing. However, because tin - a common solder metal - is used as the filler in all three combinations, the term diffusion soldering is used here to describe them.

The three diffusion-soldering processes developed are remarkably process-tolerant. They will operate successfully as long as the minimum necessary temperature is exceeded, a sufficient compressive loading is applied (>1 MPa, equal to a kilogram load acting on a square millimetre area) and that the operation is carried out in a sufficiently oxygen-free atmosphere (vacuum, nitrogen or argon), if fluxes are not used.

The resulting joints are thin and void-free and there is essentially no edge spillage, as mentioned above. As the joint homogenises to the solid solution of the base metal, the shear strength tends to values approaching or exceeding 100 MPa. Clearly, as the final composition of the joint is either substantially copper, silver or gold, the joints will have a remelt temperature that is considerably higher than the original joining temperature.

INITIAL ASSEMBLY TRIALS

Although diffusion soldering has been applied to the joining of high-power semiconductors in the past [(12)], multilayer structures have not been built by this method hitherto. A stack comprising 12 layers of tool steel were used in an initial assembly trial. These laminations were electroplated with 11 μm of silver followed by 2μm of tin. The layers were assembled together and placed in a hot press. A pressure of 3MPa was applied and the assembly heated to 525^{0}C for 1 hour in a vacuum of 2.5MPa. A portion of the assembly was then examined metallographically after being sectioned. Fig. 3 shows several layers with the diffusion-soldered joints visible. It can be seen that the metal in the joints is homogenous. Fig. 4 shows a single joint. There are no additional phases present indicating that the solder has fully diffused, forming primary silver.

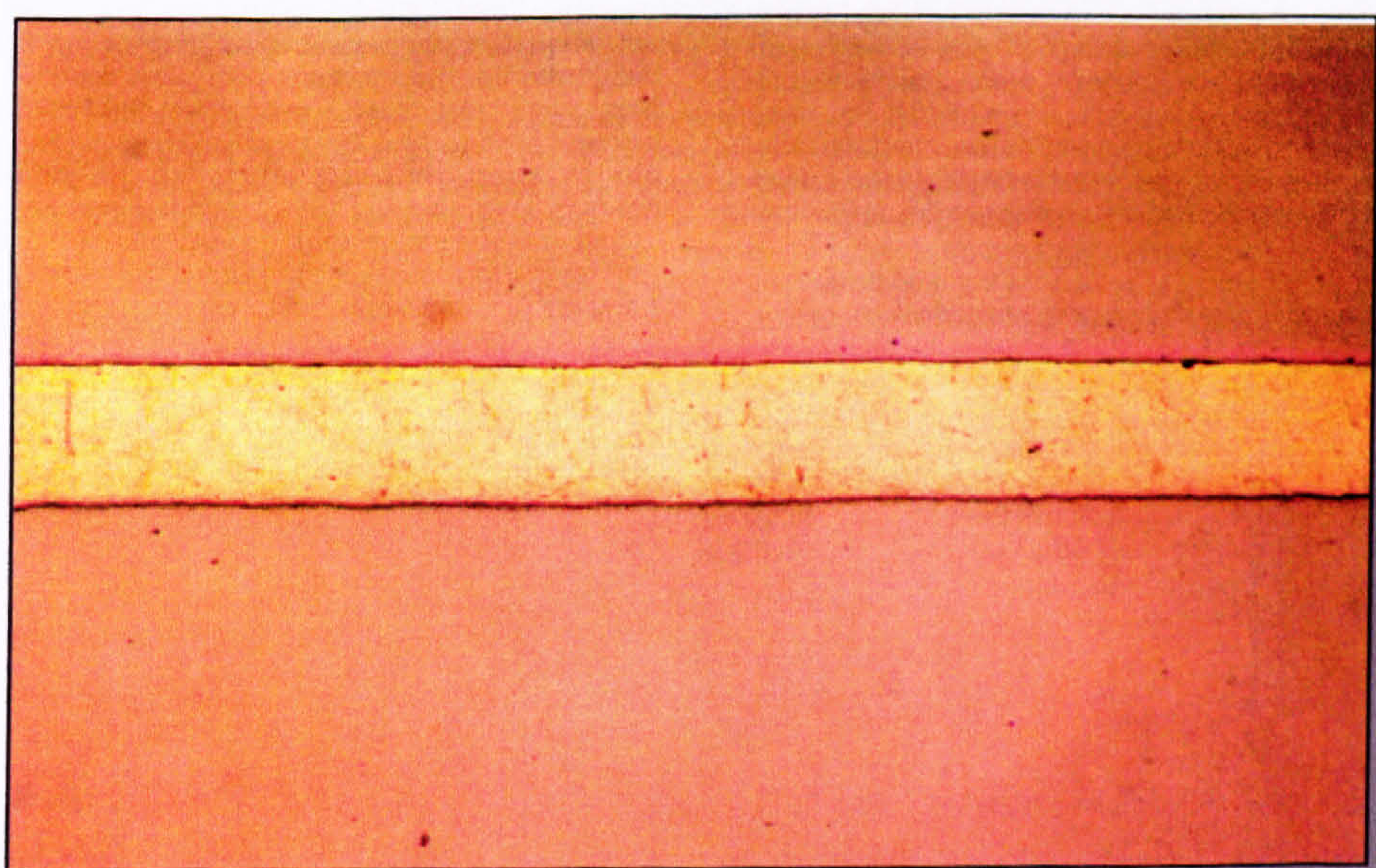


Figure 4. A single diffusion-soldered joint taken from the stack (X1000)

Fig. 5 shows the edges of the assembly. It can be seen that the joints are filled to their very edges. It is clear from the micrographs that the thickness of all the joints is the same. Diffusion soldering thus offers a highly controlled approach to joining laminations and the thickness of the joints can be taken into account in a controlled manner during the software 'slicing' process. This demonstrates that tight dimensional tolerances can be achieved by this method. The secret of obtaining controlled joint thickness lies in applying the electroplated layers-in a very controlled fashion. It is important that plating conditions are such that excessive build-up of deposits at corners and edges is minimised and that the thickness of the deposits is closely monitored and controlled.

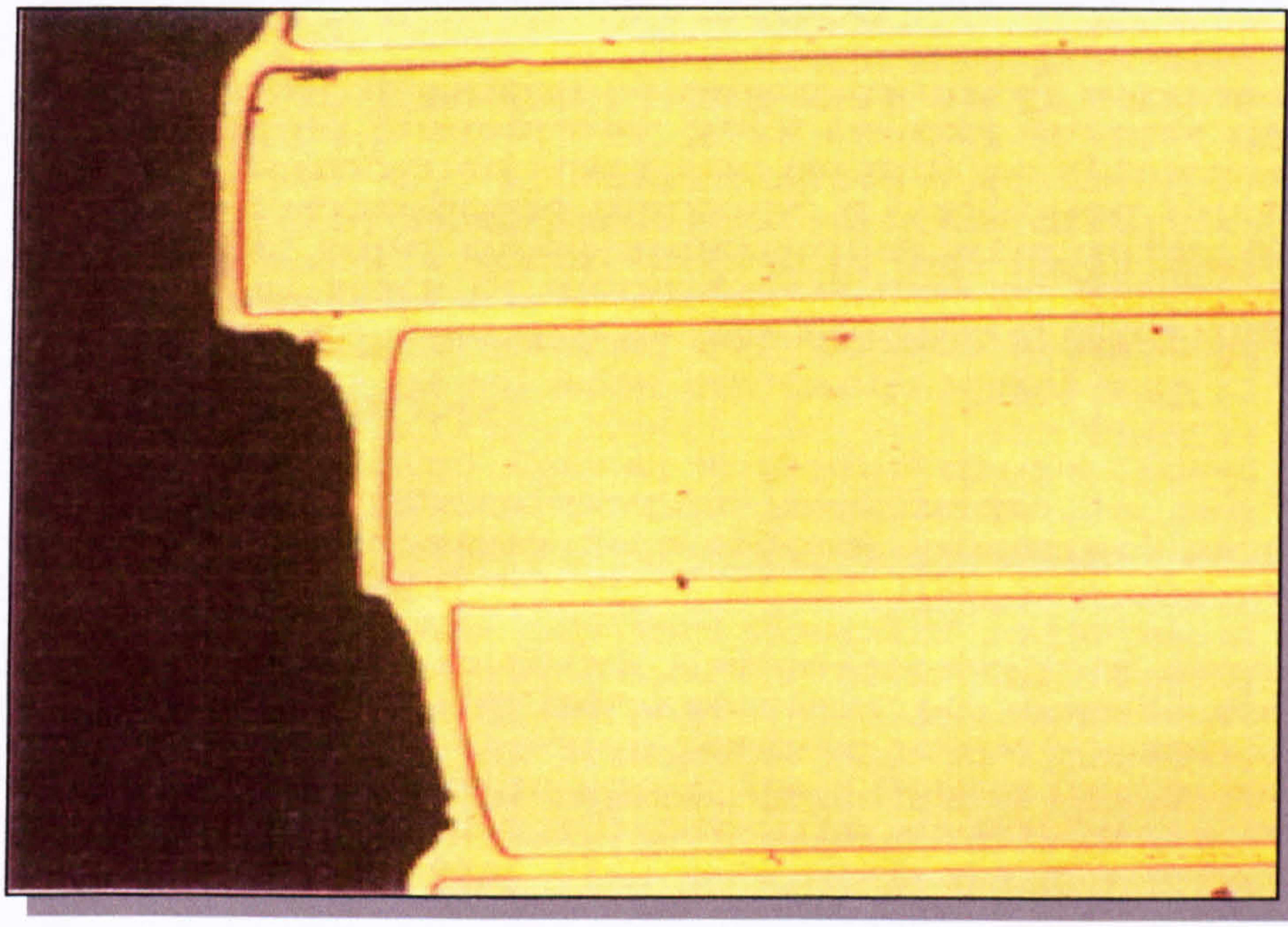


Figure 5. Edges of the diffusion-soldered stack showing good edge fillets (magnification: x 80)

The coatings were applied by electroplating, with the laminations maintained in the plating bath at an orientation relative to the anode chosen to limit the electric field at the corners and edges. In this manner, it was possible to achieve a uniform layer of the electro-deposit on the laminations.

TEST-TOOL FABRICATION

The tool required for USCAR was a simple block with an internal cavity. Fig. 6 shows the final tool design. The test tool was designed to examine the capability of the tool to withstand several thousand cycles of immersion into molten aluminium followed by cooling of the tool by high-pressure water flow within the internal cavity. This simulates the typical conditions experienced by an aluminium die-casting tool. The laminations were joined by diffusion soldering silver and tin coatings electroplated onto each element. As with all rapid prototyping methods, the process began with a 3-D CAD design. Special software was used to 'slice' the design into elemental layers that represent the cross-sectional area details of the component.

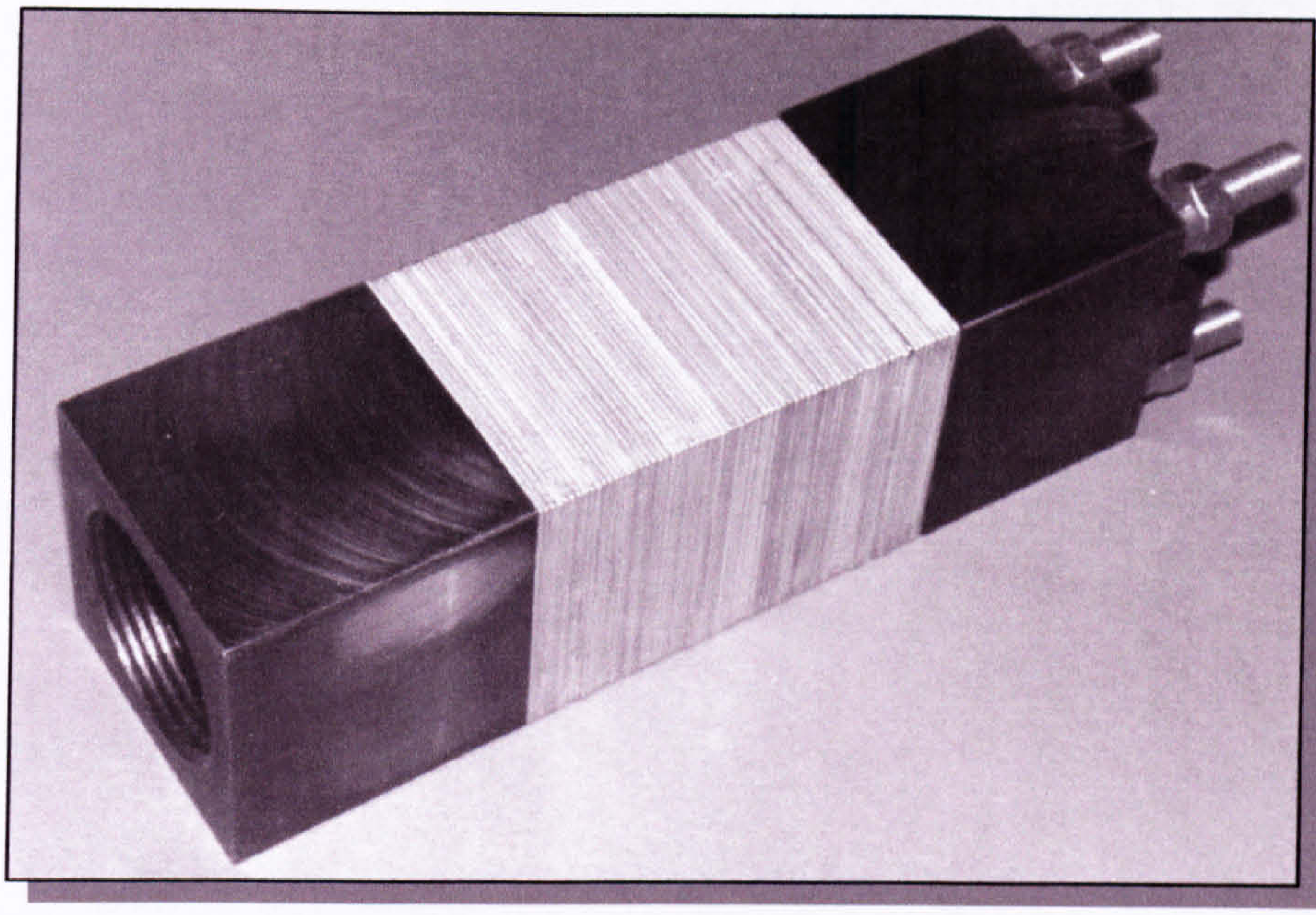


Figure 6. The final assembled tool

Each layer was produced from the 'slice' information by guiding a CO^2 laser to cut a sheet of tool steel, 1 mm thick, into the appropriate profile. When all the layers were cut, they were electroplated with 11μm of silver followed by 2μm of tin. Thickness uniformity of the electroplated layers was strictly controlled to ensure a constant joint thickness for each layer. The coated laminations were then stacked onto the base plate using the studs for alignment. The top plate was clamped to the assembly using springs possessing high temperature resilience. Sufficient torque was applied to the fixing nuts to give a total compression on the laminations of at least 1 MPa.

The clamped assembly was then loaded into a furnace filled with a protective atmosphere of nitrogen and heated to 650^{0}C for a period of 6 hours to ensure that the reaction resulted in the formation of a silver phase with tin in solution. No leakage was observed when the cavity was subjected to a water pressure of 10 kPa.

Currently, the life testing of the tool has not yet been completed, although a request for further tools constructed by this method has been made.

CONCLUSIONS

It has been shown that by using diffusion soldering, a multilayer stack of metal sheets may be joined to form large, solid three-dimensional structures. By employing appropriate methods, a controlled thickness of electroplated silver and tin may be applied to the individual laminations. Such control enables the formation of diffusion-soldered joints of a known thickness; structures of high dimensional precision may then be realised by this method.

The joints produced using this MELOM approach have shear strengths approaching that of primary Silver (100MPa). Although the joining temperature is only 650°C, the joints produced will remelt only at temperatures approaching the melting point of silver (962°C). Such joints are suitable for use in tools required for the pressure die-casting of aluminium and zinc.
This approach offers enormous advantages in speed of production for large-scale prototype tooling. Indeed, by using appropriate finishing methods to remove the 'staircasing' of the metal elements, such as electro-discharge machining, such tools could be used in production. Although only the silver-tin system has been used in these trials, copper-tin is equally applicable and would offer the advantages of lower materials cost and a higher joint remelt temperature. Future plans include an examination of the use of the copper-tin system in the further development of MELOM, which produces tools and other objects directly in metal.

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The Use of Laminate Tooling for the Production of Prototype Pressure Die-Cast Dies.

R.C.Soar and Professor P.M. Dickens

Proceedings from: Time Compression Technologies Conference 1998, 13-14th October, Nottingham, UK, pp332-343.

ABSTRACT

The use of Laminate Tooling for the production of prototype pressure die-cast dies is well into the experimental stage. This paper will cover recent work that tries to establish the design limitations for a laminate pressure die-cast die, in particular, what is the maximum height/aspect ratio of a laminate up-stand feature within such a die before deflection and ingress of molten material permanently damage it.

INTRODUCTION

Laminate Tooling uses the layered data from a 3D CAD model of a tool. Each slice is exported via DXF to a laser-profiling machine. Each of the DXF files defines one laminate of the tool and all are nested to fit a pre-defined sheet of steel, aluminium, stainless steel, etc. After cutting they are de-burred and assembled into the finished tool. The benefits of Laminate Tooling[1] can be summarised as follows:

- The production of large-scale tooling, as the size of each laminate is only restricted by the size of the laser profiling bed.
- The inclusion of conformal cooling channels for decreased cycle times.
- The replacement of damaged or worn laminates.
- The exchange of laminates for different profiles within a tool.
- Low cost and time of production, as there is little capital layout due to the abundance of laser sub-contractors.

Laminate Tooling is becoming increasingly attractive to die-casters because of the huge expense of conventional die production. Dies commonly require modifications after manufacture; and there are problems encountered when reducing hot spots within a die. Conventional die manufacturing may only allow for one attempt to get the design correct and the die must also be dedicated to producing many tens of thousands of parts to justify the cost.

The rapid increase in the use of die-casting, particularly with aluminium has resulted in larger dies, running faster. In addition, product lines can change annually requiring new tooling. Laminate tooling has the potential to offer low cost, large scale dies for limited runs. They allow the die-caster to produce prototype tools that can be run on the actual die-cast machines, which makes possible the study of:

- Material flow throughout the die.
- The formation of hot spots and soldering
- Effectiveness of cooling channels;
- Ejector pin layouts; vortices; overflows; gating etc.

By exchanging laminates within the die many iterations can be carried out before the final die design is set. Some of the groups involved in the development of Laminate Tooling around the world include: Stratoconception®[2], CIRTES (France); CRIF (Belgium); De Montfort University[3], Warwick, Leeds & Liverpool Universities (UK); MIT[4], Clemson[5] & Ohio State[6] Universities (USA); DTI[7] (Denmark); Tokyo University[8] (Japan); most are backed by major automotive and aerospace sponsors keen to see a viable process.

Over the last year tests have been conducted on an experimental laminate test die to establish the point at which ingress of pressurised molten aluminium occurs within an array of up-stand features within a laminate die for the pressure die casting of aluminium LM24

The methodology for this experiment has been covered in a previous report presented at The Solid Freeform Fabrication Symposium, University of Texas at Austin[9], which outlines the methodology and stages that have been necessary to achieve the data in this report. This first stage in the experiment had two elements. The first was to establish whether or not a laminate tool could withstand pressure die-casting and the second to establish what degree of deflection occurs and where those forces are operating in the laminate die that the designer would have to be aware of. The final stage to this series of experiments will be to establish the specific points of ingress of molten aluminium between individual laminates of any material, which would lead to premature tool failure.

METHODOLGY

The pressure die-casting (PDC) machinery used was a pneumatic EMB 100 ton in cold chamber set up. The experiment required a run of ten uninterrupted shots into a laminate test-die (ten shots was the maximum material that the 'bale out' furnace could supply without re-charging). The laminate test-die contained a range of up-stand features that would deflect proportionally depending on how much resistance they placed in the path of the incoming aluminium.

The range and layout of the up-stand arrays is shown as a plan and cross-sectional view in Figure 1 and 2. The test die had 16 individual up-stands with the last laminate in that up-stand protruding, by a pre-defined amount, into the incoming flow of molten aluminium. The heights ranged from 0.25mm to 6.00mm, with many of the heights being repeated in both the upper and lower halves of the die as a form of cross checking. The material used was LM24 aluminium alloy (Al-Si8-Cu3) which is a standard die-casting material around the world. The finished die is in Figure 3.

Pressurised molten material enters the die from the centre of the up-stand arrays and fans out through two tapered gates to the upper and lower half of the die. Below each up-stand in the test-die is stamped a corresponding letter from 'a-p'. As the castings were to be cut up later it was necessary to mark each up-stand so that any deflection/ingress could be accurately recorded. Each of the ten castings from each run were given an identification number from 1-10 that will appear in the table of results.

Looking more closely at the effect on the laminate up-stand, its deflection and possible ingress. At a certain height there will be enough force to deflect this laminate to cause ingress of molten material between itself and the laminates it abuts. Figure 4 shows a cross section of the two extremes of the up-stand arrays that will be created in the test die.

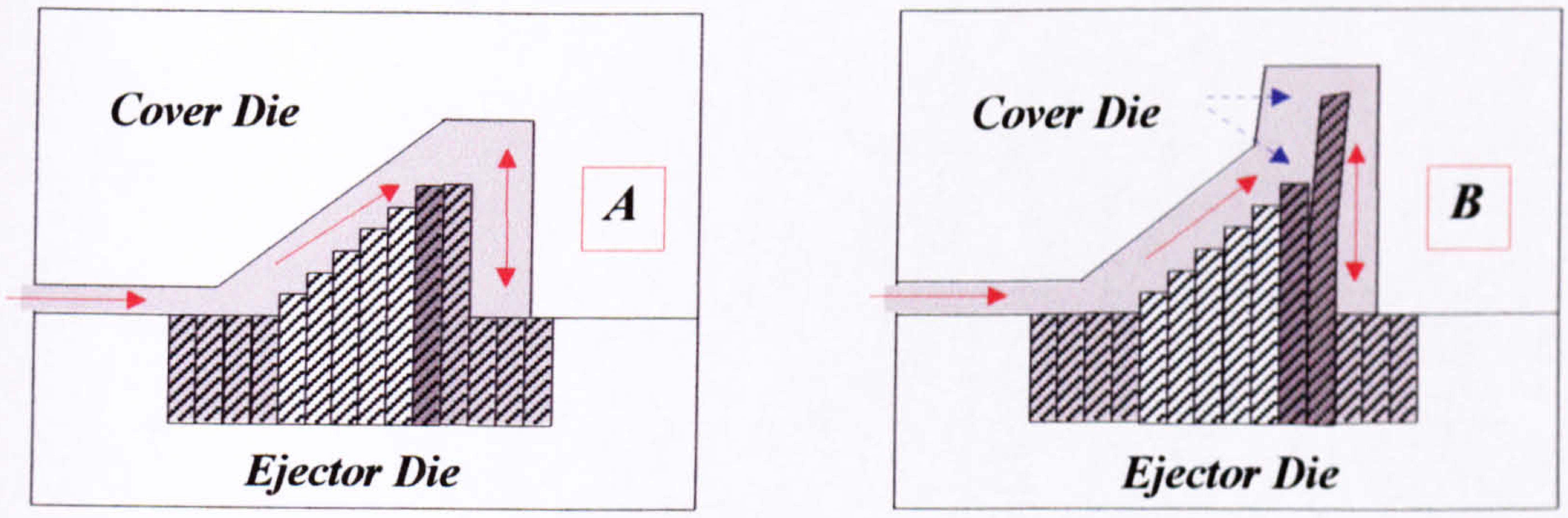

Figure 4. Effects of deflection on laminate up-stands

The simplified illustration *(A)* shows molten material entering from the left and being forced upward at 45^0 over a ramp formed by the laminates. Each laminate stands 1 mm higher than the laminate on the left. This design will not incur any deflection as the laminates in the up-stand support each other and the end laminate does not protrude into the flow of molten metal.

On illustration *(B)* material enters from the left and is directed up the laminate ramp where it will strike the last laminate before passing over and around it. This laminate will deflect but may move to the upright position again, due to its elasticity/rigidity, before the cast freezes. Trying to measure this deflection as it occurs in the die would be impossible; this measurement can only be taken by examining the casting after removal from the die. If the last laminate deflects enough then there will be ingress of aluminium that will freeze between the laminates. When the cast is removed from the die a 'witness mark' will remain that can be measured as a direct indication of the amount of deflection that occurred in the last laminate, as shown in Figure 5.

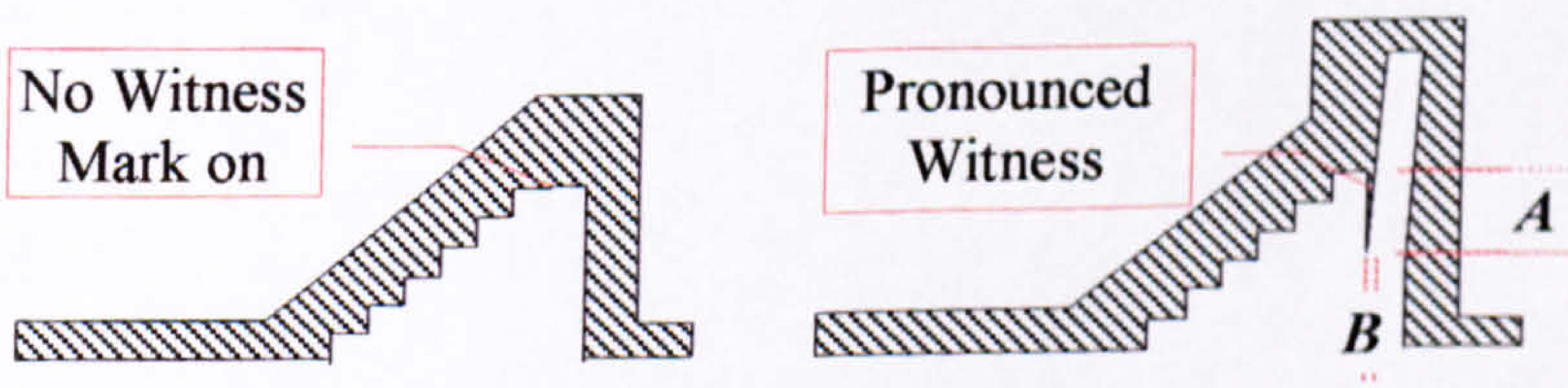

Figure 5. Measurable witness marks on resultant aluminium casting.

THE RESULTS

From the very first runs it became clear that the laminate test die could repeatedly produce clean castings, as shown in Figure 6. Even in the worst cases where ingress between the laminates occurred the laminate structure was forgiving enough to allow continued use. Doubts as to the effectiveness of an un-bonded laminate structure for pressure die-casting was quashed and six months on the die is still in use.

As regards the degree of ingress for a given up-stand height, the ten castings that came off the run were cut longitudinally so that any visible witness marks could be clearly measured from the side.

No witness mark indicated that no ingress/deflection had occurred for that particular up-stand height, for that particular location in the die. Measurement was done with a co-ordinate vernier microscope on 10x magnification. Cross hairs allowed measurements via vernier screws that independently controlled movement of the specimen in the x and y direction. Resolution was approximately 0.01mm.

The measured ingress on each up-stand for each casting from 1 to 10 appears in Table I. The casting number is located on the left column. The individual up-stands 'a' to 'p' are shown in the top row of the two tables along with the height of the laminate up-stand protrusion above the laminate ramp ranging from 0.25mm to 6mm.

ANALYSIS OF THE RESULTS

The information in Table I is important particularly when observing deflection of up-stand 'k' (4mm) and to a lesser degree up-stands 'f' (3mm) and 'e' (5mm). It was thought that the up-stand at 'k' had been damaged during transport and might explain the very large ingress that occurred throughout the run. In reality, up-stand 'k' began the run showing no ingress until casting no.2 where upon it began to rise sharply to the point that, by the end of the run the laminate was permanently deformed.

Graph I shows the mean ingress plotted over the range of up-stand heights. Ingress at each height is clearly erratic and does not increase gradually as was expected. Molten aluminium does not readily wet steel (though it will solder in extreme circumstances). Its behaviour is analogues to mercury, which implies that small gaps that appear through deflection will not readily fill with molten material until the gap reaches a certain distance. Over this point material will freely move into the gap and freeze and this effect should appear as a jump in the graph at some point.

From the graph above it was clear that no such jump occurred (even though there is a large spike at 4.00mm on position 'k'). It would be impractical to take an average ingress reading of all the points on this graph to establish the point at which ingress occurred.

CHANGE IN INGRESS IN THE 5-6mm RANGE.

The randomness of the mean ingress readings for each up-stand was disappointing and required a closer look at what may have been causing such a fluctuation in the readings. Mean data, bar charts were plotted showing the mean ingress for each up-stand superimposed over the actual position of each up-stand within the die. There were too many charts too reproduce here but it was clear that ingress/deflection was highest in the up-stands located in the centre section of the die (b, c, f, g, o, n, k & l).

There is a phenomenon, within pressure die-casting, which observes that the type and cross section of inlet gate; the distance of features from the inlet gate and the shape of the die cavity can affect how molten material flows into and around a die. In studies it has been shown that molten aluminium will try to move vertically up the die, strike the back wall of the cavity and fill the cavity from the rear as well as the front.

If uneven filling of the die cavity could be shown then it would go some way to explain the drop-off in ingress towards the extremities of the test-die. By forming incomplete castings from the test-die it was possible to analyse how molten aluminium flowed through the die prior to a complete fill.

Analysis showed that even though the flow was being spread evenly over the cross section of the fanned inlet gate its progress through the die was not parallel as was intended. There was a clear surge of material up and over the centre up-stands, after which it would start to spread out behind the backs of the up-stands on the extremities of the die at up-stands 'a, l, i & d'. At some point it would chill to such a degree that material would begin to fill from the front over extremities 'e, p, h & m'. This resulted in material striking these latter up-stands from both the front and rear simultaneously. The effect would be to counteract any possible deflection at these points resulting in zero ingress at the 5 to 6mm up-stands.

REJECTING THE DATA FROM THE EXTREMITIES

Establishing deflection figures on the extremes of the die to be false resulted in their rejection so that deflection and ingress could be established for those laminates from the central section of the die. Plotting this data in up-stand height order and averaging where two up-stand heights are repeated (i.e. there are two 3mm and 4mm readings) a line graph can be produced such as Graph II

The data shows an unexpected degree of linearity with a rise in ingress above the 2 mm point. This implies that for 1mm thick H13 tool steel sheet, there is a design limitation of 2mm for any individual laminate that protrudes above this height above its neighbouring laminates. Above this point inter-laminar bonding will be required. The 4mm data do vary greatly mainly due to the excessive deflection that was discussed earlier at up-stand 'k' (4mm). The data plotted from just the upper or lower half of the die does not show the same results. It was only when the data was combined that the graph above appeared. This fact implies more runs are necessary to establish consistency in these results.

CONCLUSIONS

From this initial study we have shown that an un-bonded laminate pressure die-casting tool performs well and, most importantly, has produced hundreds of castings to date. We will continue using this tool to establish just how many castings are possible from it. We have also shown that when it comes to the design of a laminate tool any isolated laminate feature that protrudes greater than 2mm above its neighbouring laminates will succumb to sufficient deflection to allow the ingress of aluminium between the laminates which will shorten tool life significantly.

The data gathered on the first clear run of ten castings definitely indicates ingress within the pre-defined range of laminate up-stands. Within the range of up-stands from 0.25 mm to 6 mm ingress occurred at no clear point within the range. Ingress tended to be dependent on the up-stands position in the die and its orientation to the inlet gate.

Further analysis revealed that around those up-stands on the extremities of the test die molten material was able to flow around the back. This effect was to negate any ingress that should have occurred at these points. This led to the decision to plot the mean ingress from up-stands towards the centre of the die. It was in this central region that it was shown that molten aluminium flowed consistently over the up-stands to give useable ingress readings. What further exacerbated these readings and cannot be shown here are a high degree of inconsistency between castings due to the age and efficiency of the die-casting machine used.

This experiment will now be repeated over many more castings to hone in on the point at which ingress between laminates can effect tool life. A new 125 tonne Frech hydraulic pressure die-casting machine has now been installed which has a high degree of repeatability and therefore more consistent readings. This data will form the basis for design limitations when producing laminate pressure die-cast tooling.

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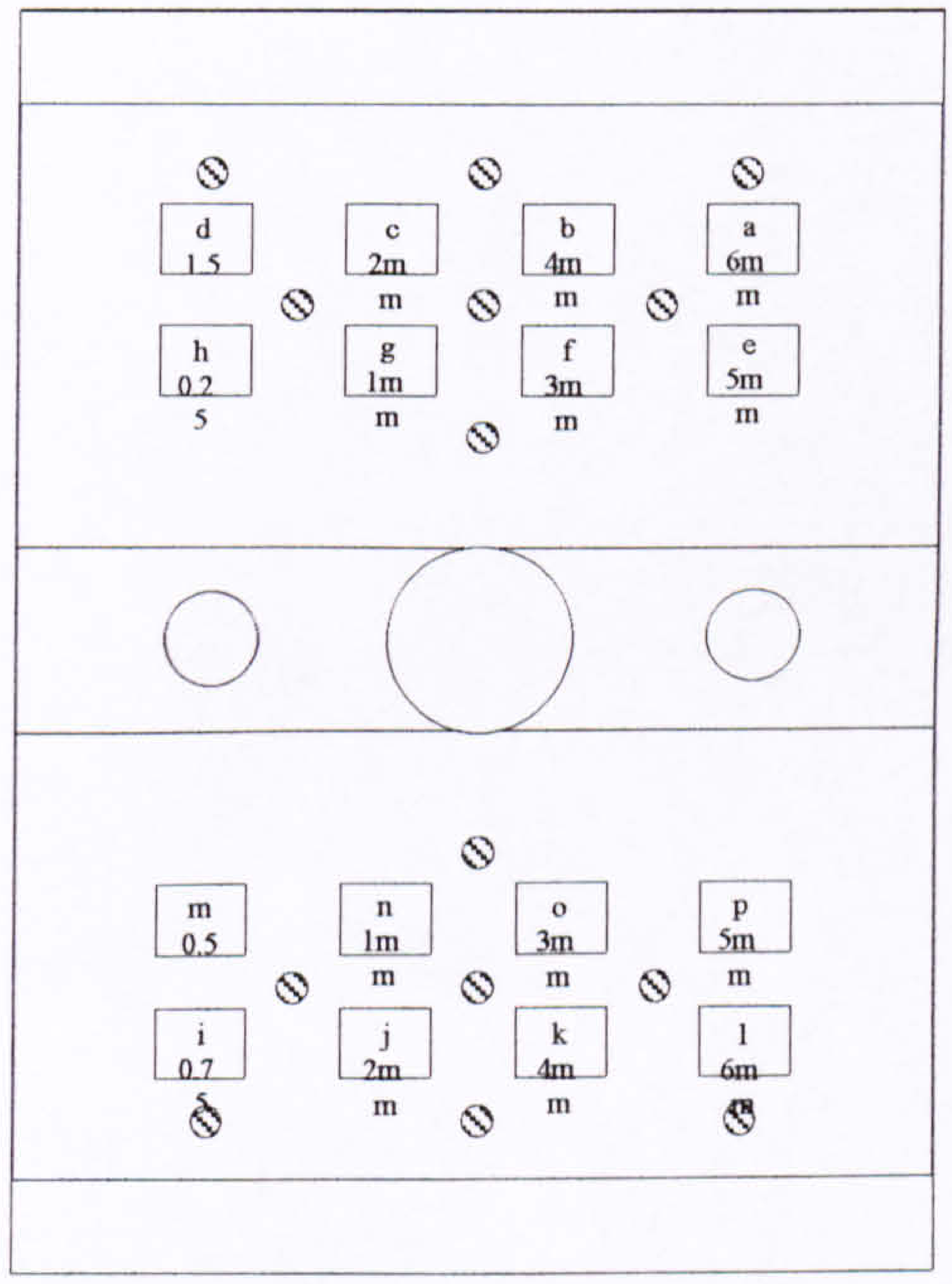


Figure 1.

Plan view of the ejector die, showing the laminate arrays. Height of each up-stand is shown in mm. The entire assembly is located into a standard bolster and held with sliding wedges for ease of disassembly.

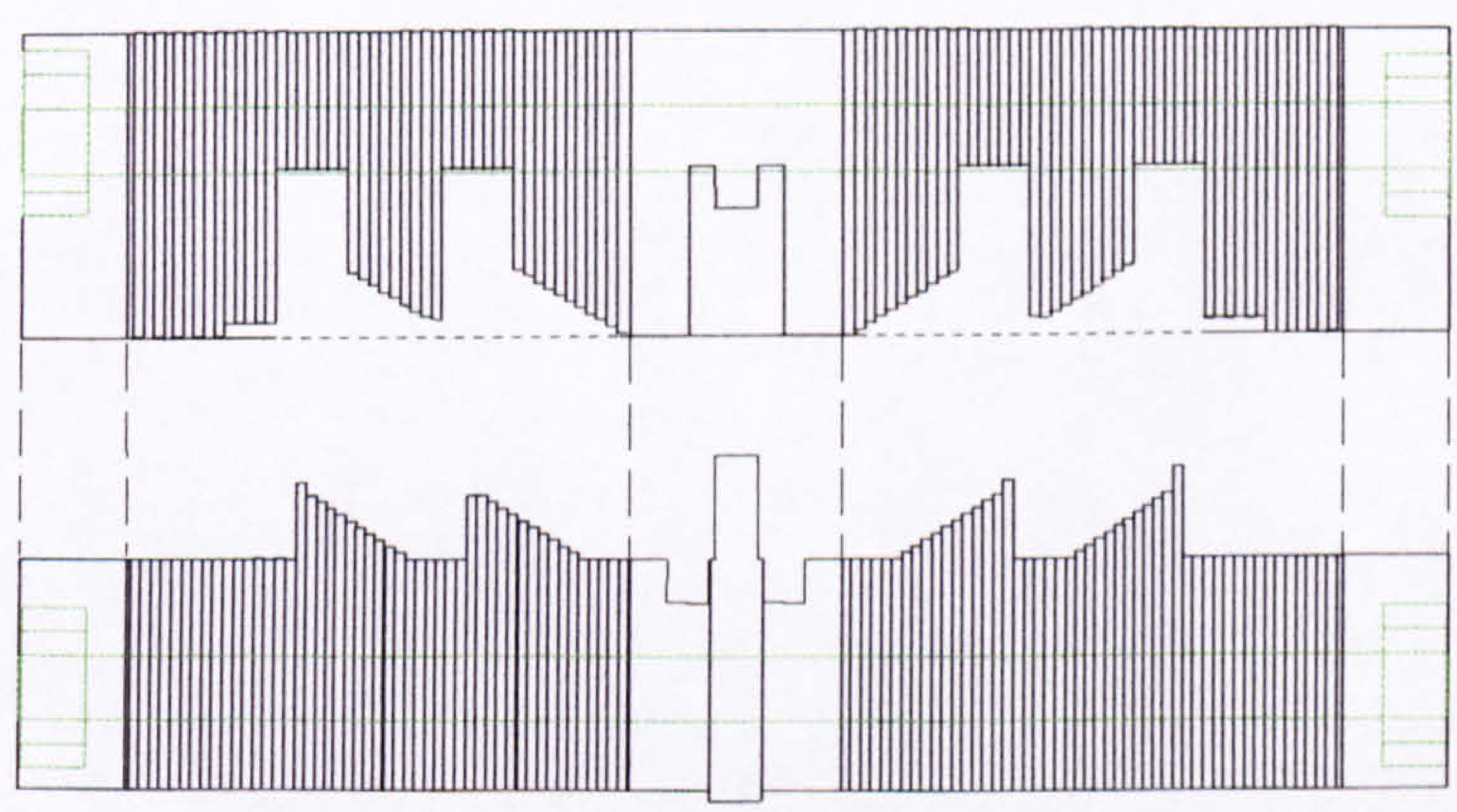


Figure 2.

Cross-sectional view of the cover & ejector die through section AA, showing the laminate arrays. Individual up-stands can be seen on lower die showing the 0, 2, 4, & 6mm laminates at the end of the ramp.

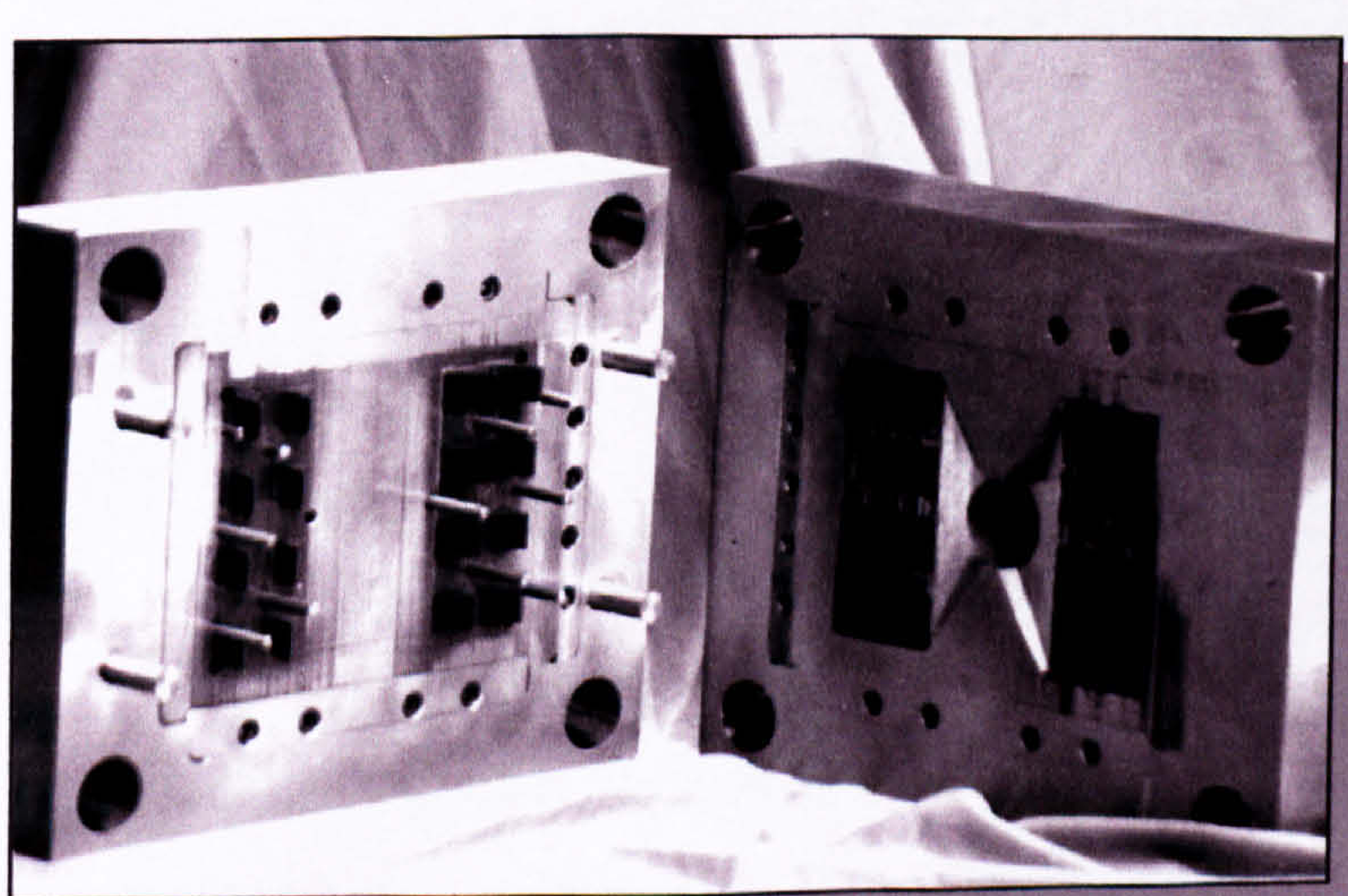


Figure 3.

Completed Laminate Test-die

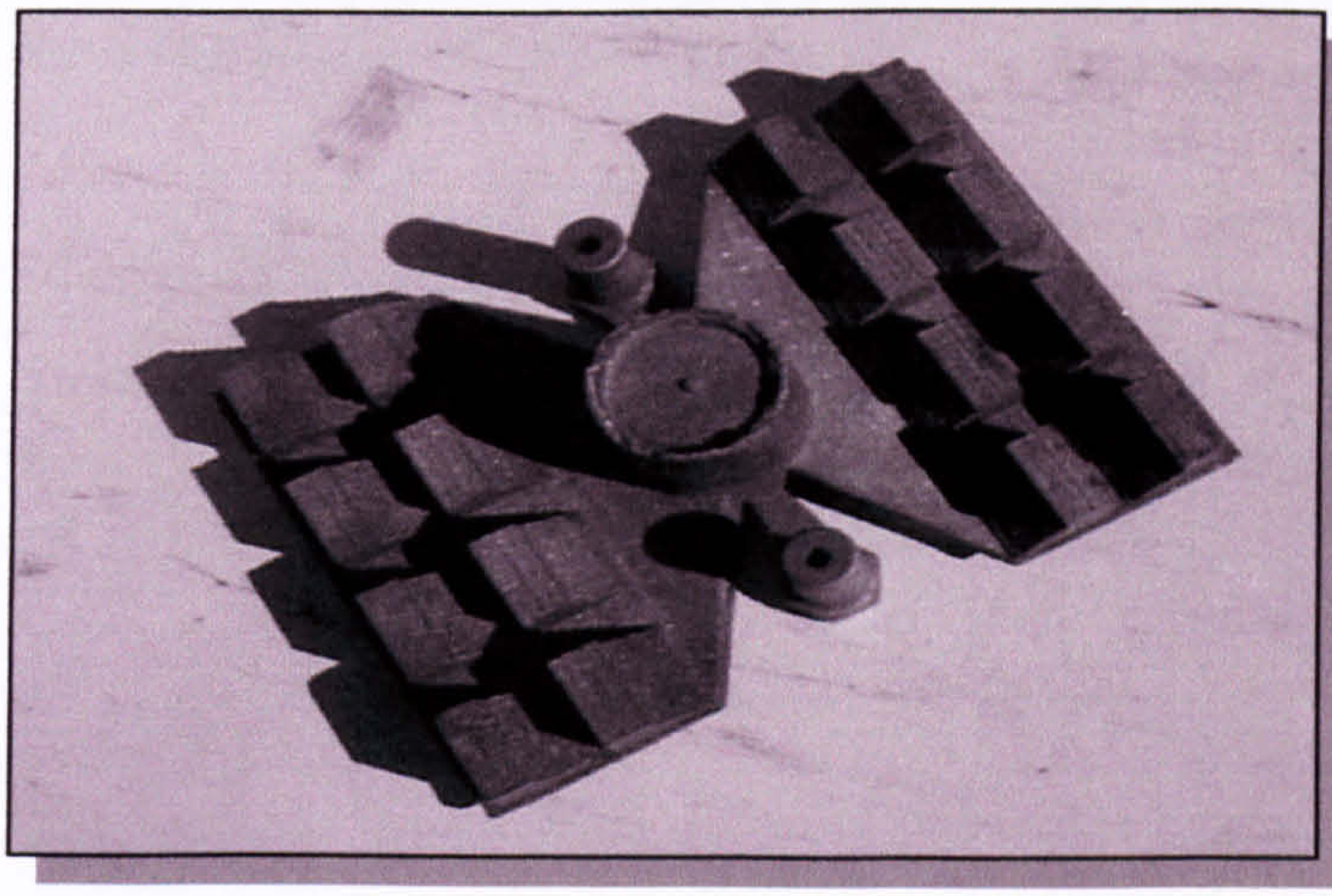


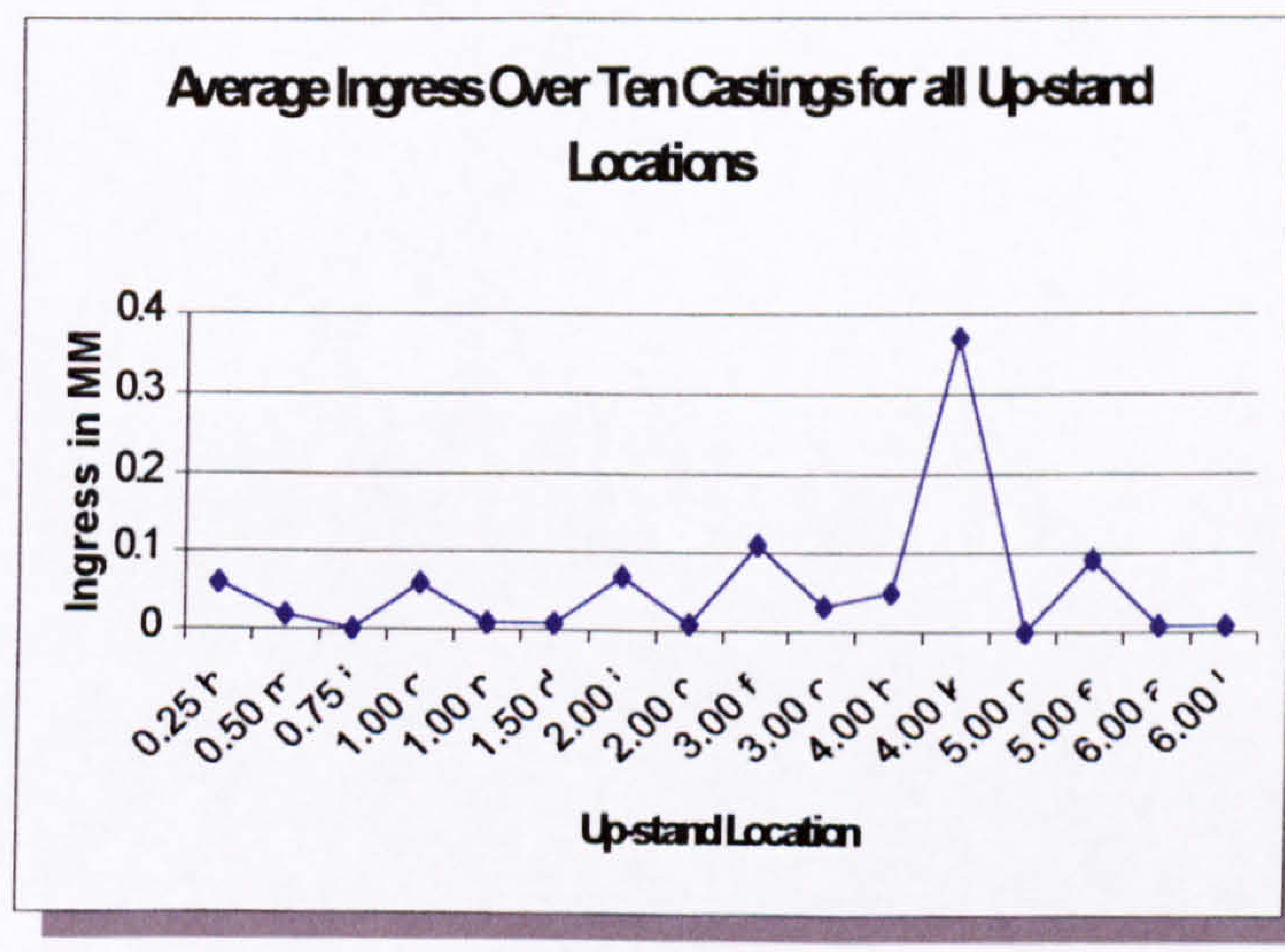
Figure 6.

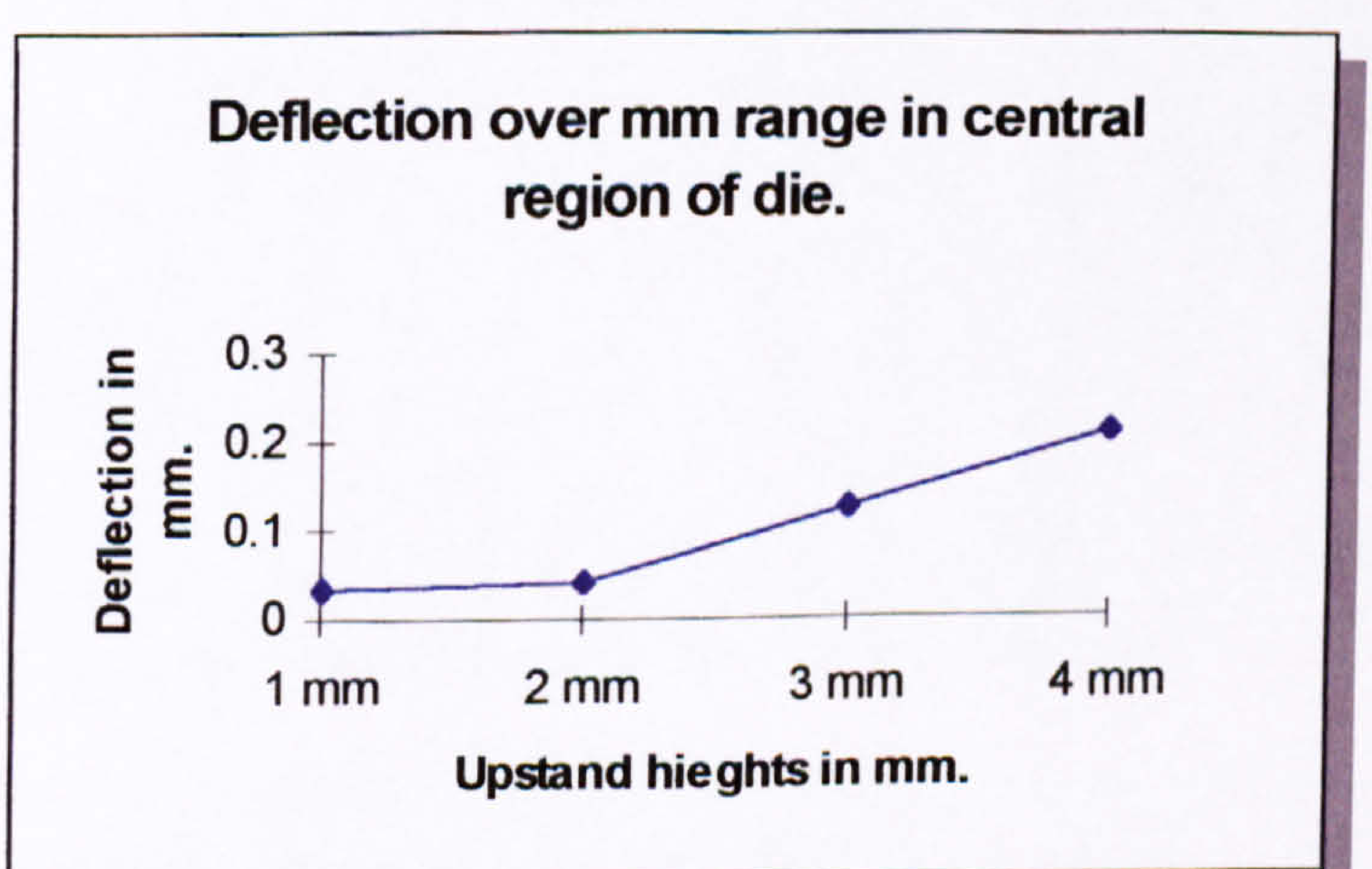
Complete casting from the Laminated test die. Die pre-heat of 175 ^{0}C with a graphite based release agent.

Graph I

Mean ingress for each up-stand. X-axis denotes progression in up-stand height from 0.25 to 6 mm. Y-axis denotes the degree of ingress, in mm, at that location in the die.

Ingress should increase gradually from left right with a small jump where ingress starts.





Graph II

Mean ingress at each up-stand height with the measurements from the extremities of the die ignored. There appears to be linearity with a sharp rise in ingress at the 2 mm mark.

This result was from one run only and more testing for consistency must be done.

Rapid Prototyping Opportunities: Laminate Tooling for Aluminium Die-casting

Rupert Soar & Professor Phillip Dickens

Proceedings from: The Aluminium '98 Conference, 23rd-24th September, 1998, Messe Essen, Germany.

ABSTRACT

Laminate Tooling is a simple and inexpensive method for the production of large, durable production tooling and prototypes. Over the last four years, extensive research has been conducted to investigate the feasibility of laminate tooling in various production and tooling applications.

INTRODUCTION

The principle of Laminate Tooling (LT) is to take the layered data of a tool, generated from a Solid CAD model and output the slices to a CNC controlled profiling machine (laser, high definition plasma or abrasive waterjet). Each of the DXF files defines one laminate of the tool and all are nested to fit a pre-defined sheet of steel, aluminium or stainless steel etc. and cut. After cutting they are de-burred and assembled, in sequence, into the finished tool.
Laminate Tooling research began some fifteen years ago in Japan by Professor Takeo Nakagawa. So successful was this venture that in 1996 Nakagawa reported that the Hanai Engineering Company in Japan had already produced their 10,000th LT[1]. To date, the feasibility of Laminate Tooling has been explored by various research groups around the world, including Glozer and Brevick[2], Schreiber and Clyens[3], Walcyk and Hardt[4], Lyett *et al*[5], all with varying degrees of success. It is only within the past few years that interest in Laminate Tooling has peaked, primarily through the need for Rapid Tooling processes and the growth of CAD.

Soar & Dickens [6] have shown that Laminate Tooling offers a fast and cost effective way by which metal tools can be produced directly from a 3D-CAD model. This simple process results in a tool with the following advantages:

- The production of large scale tooling as the size of each laminate is only restricted by the size of the laser profiling bed.
- The inclusion of conformal cooling channels to increase running speeds of the tool.
- The replacement of damaged or worn laminates.
- The exchange of laminates for different profiles within a tool.

- Low cost and time of production, low capitol outlay due to the abundance of laser sub-contractors.

AN OVERVIEW OF THE RESEARCH

The first work done was with Simco Industries and Ford, Utica[7]. The tool produced was a large eight-chamber urethane foam-forming tool for the production of car door impact devices. The tool was constructed from 1mm thick aluminium sheet that was laser cut to give over 1600 individual laminates that made up both the upper and lower halves of the mould. Individual laminate profiles were approximately 1000mm×100mm. The tool has been in full production for over two years at the Utica plant producing well over 100,000 parts.

Following the success of this work the next investigation was to identify other applications for Laminate Tooling. Two tools were constructed. The first was for thermo-forming ABS sheet and the second was an injection mould tool for polypropylene. The thermo-form tool used low carbon, 1mm thick, steel sheet and the injection mould tool used 0.5mm, high carbon steel, sheet. The latter was to establish the level of detail that would be possible by using thinner sheet thus minimising the level of stepping. This tool needed no bonding and worked with no permanent ingress of molten material between any of the laminates.

This work was closely followed by a study of the elimination of stepping from the surface of a laminate tool [8]. By using the same CAD model as was used to generate the laminate mould, a stereolithography model could be made defining the cavity in the tool. This was plated with copper and subsequently used as an EDM electrode to remove the stepping from the inside of the laminate tool. This proved successful, but was limited by the size that the electrode could be made.

As the research progressed, Laminate Tooling became attractive to die-casters due to the huge expense of conventional die production. Die-cast tooling commonly requires modification after manufacture. This may be due to incorrect gate orientation or hot spots within a die. Die-casting, by its very nature, only gives the toolmaker one attempt to get the design correct. Laminate Tooling has the potential to offer low cost, large scale dies for limited runs. Even if they cannot perfectly match the performance of a conventional die they can allow the die-caster to produce prototype tools that can be run on the die-cast machines. This makes possible the study of material flow throughout the die, formation of hot spots and soldering, the effectiveness of cooling channels, ejector pin layouts, vortices, overflows, gating and the list goes on. By changing laminates many iterations can be carried out before the final die design is set. The program of research has taken four routes to achieve the aim of viable laminate tooling for pressure die-casting. These routes are:

- Die design considerations and selection of suitable sheet material.
- Testing laminate stacks against failure through thermal cycling/stress.
- Assessing the fundamentals of laminate die behaviour to withstand deflection and ingress of molten aluminium.

- The bonding of laminates in extreme environments.

There are various ways that a laminate tool can be constructed and so the first stage in this investigation was to consider the design implications when constructing a laminate tool. Time was also spent, establishing suitable sheet material and sheet thickness for use in these applications. After considerable effort all test dies are now constructed from 1mm thick, cold rolled, H13 tool steel. Sources in both Japan and Austria can supply material with reasonable notice.

The second route was to look at the behaviour of laminate structures when used in pressure die-casting. This work has been done in conjunction with the United States Committee for Automotive Research (USCAR). The third route forms the basis of fundamental research into laminate die behaviour under extreme conditions such as those found in pressure die-casting[10]. The fourth route is underway in conjunction with GEC Marconi, Hirst Division[11], and explores the bonding of laminates in a die.

CONCLUSIONS

Where large tools or prototypes are required the use of cut laminates offers a cost effective and fast method to get to the final design. Computer modelling is becoming increasingly more available to the designer but there is still a long way to go before it becomes a reliable modelling tool. At present there is not considered a substitute for a test rig. Companies like Ford have long realised that a fast way to mock up the cooling assembly on an engine block is to construct the part from slices of steel that have been bonded together. Where an aesthetic finish is not essential and large scale is required, at present, there is no real substitute for the laminate structure.

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Figure 1. The laminate Simco tool in production at Ford

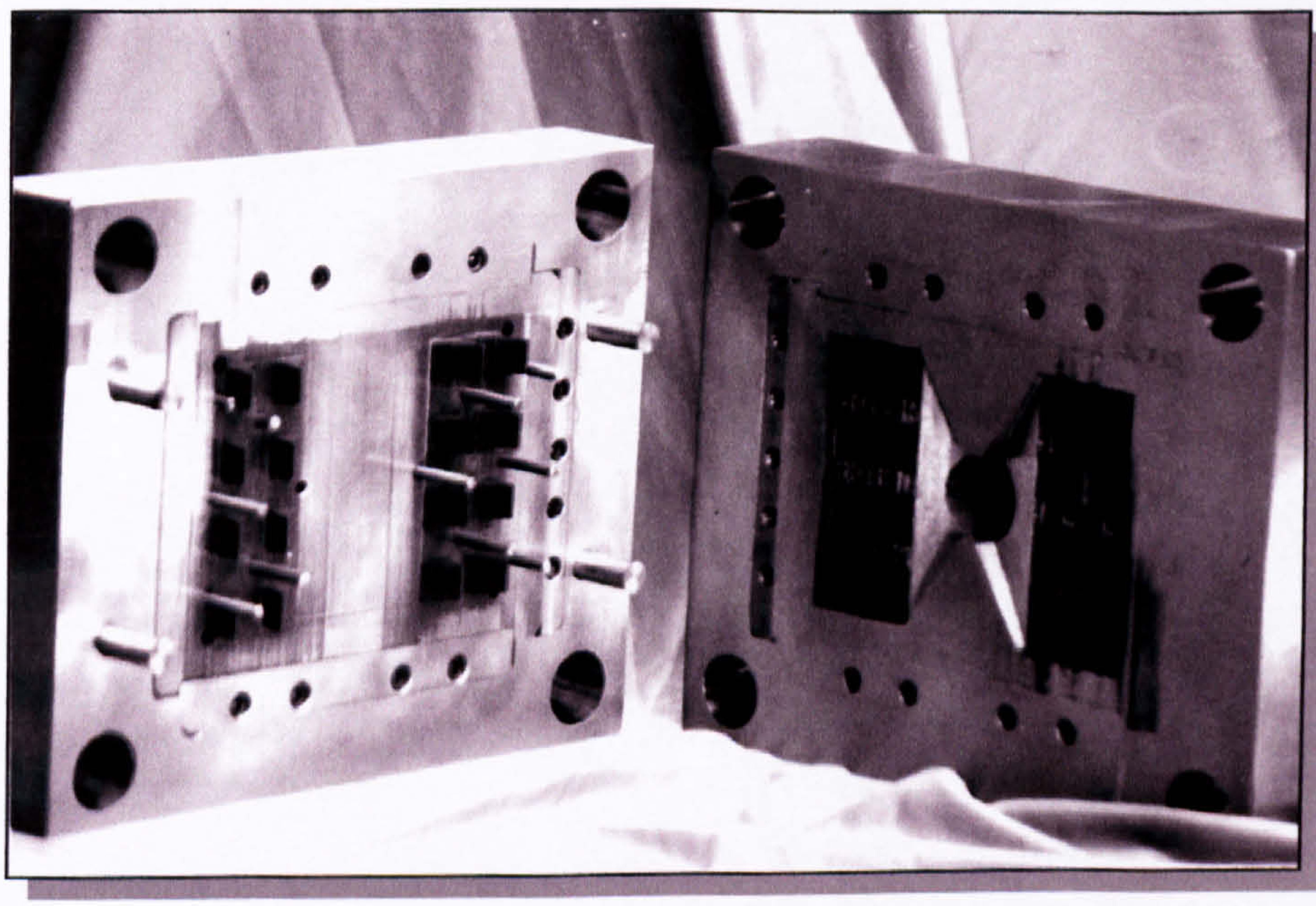

Figure 2. The laminate pressure die-cast test-die

Large Scale Prototypes & Tooling from CNC Laser Cut Sheets or 'Laminate Tooling'

Rupert Soar & Professor Phillip Dickens

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ABSTRACT

Laminate Tooling is a simple and inexpensive method for the production of large, durable production tooling and prototypes. Over the last four years, extensive research has been conducted to investigate the feasibility of Laminate Tooling in various production and tooling applications.

INTRODUCTION

The principle of Laminate Tooling (LT) is to take the layered data of a tool, generated from a solid CAD model and output the slices to a CNC controlled profiling machine (laser, high definition plasma or abrasive waterjet). Each of the DXF files defines one laminate of the tool and all are nested to fit a pre-defined sheet of steel, aluminium, stainless steel etc. machine After cutting they are de-burred and assembled, in sequence, into the finished tool.

Laminate Tooling research began some fifteen years ago in Japan by Professor Takeo Nakagawa. So successful was this venture that in 1996 he reported that the Hanai Engineering Company in Japan had already produced their 10,000th laminate tool[1]. To date, the feasibility of Laminate Tooling has been explored by various research groups around the world, including Glozer and Brevick[2], Schreiber and Clyens[3], Walcyk and Hardt[4], Lyett *et al*[5], all with varying degrees of success. It is only within the past few years that interest in Laminate Tooling has peaked, primarily through the need for rapid tooling processes and the growth of CAD.

Soar & Dickens[6] have shown that LT offers a fast and cost effective way by which metal tools can be produced directly from a 3D-CAD model. This simple process results in a tool with the following advantages:

The production of large scale tooling as the size of each laminate is only restricted by the size of the laser profiling bed.

- The inclusion of conformal cooling channels to increase running speeds of the tool.

- The replacement of damaged or worn laminates.
- The exchange of laminates for different profiles within a tool.
- Low cost and time of production, low capitol outlay due to the abundance of laser sub-contractors.

AN OVERVIEW OF THE RESEARCH

The first work done was with Simco Industries and Ford, Utica[7]. The tool produced was a large eight chamber polyurethane foam-forming tool for the production of car door impact devices. The tool was constructed from 1mm thick aluminium sheet that was laser cut to give over 1600 individual laminates that made up both the upper and lower halves of the mould. Individual laminate profiles were approximately 1000mm×100mm. The tool has been in full production for over two years at the Utica plant producing well over 100,000 parts.

The next stage was to investigate the use of Laminate Tooling for other applications. Two tools were constructed. The first was for thermo-forming ABS sheet and the second was an injection mould tool for polypropylene. The thermo-form tool used low carbon, 1mm thick, steel sheet and the injection mould tool used 0.5mm, high carbon steel, sheet. The latter was to establish the level of detail that would be possible by using thinner sheet thus minimising the level of stepping. This tool needed no bonding and worked with no permanent ingress of molten material between any of the laminates.

This work was closely followed by a study of the elimination of stepping from the surface of a laminate tool [8]. By using the same CAD model as was used to generate the laminate mould, a stereolithography model could be made defining the cavity in the tool. This was plated with copper and subsequently used as an EDM electrode to remove the stepping from the inside of the laminate tool. This proved successful, but was limited by the size that the electrode could be made.

As the research progressed, Laminate Tooling became attractive to die-casters due to the huge expense of conventional die production. Die-cast tooling commonly requires modification after manufacture. This may be due to incorrect gate orientation or hot spots within a die. Die-casting, by its very nature, only gives the toolmaker one attempt to get the design correct.

Laminate tooling has the potential to offer low cost, large scale dies for limited runs. Even if they cannot perfectly match the performance of a conventional die they can allow the die-caster to produce prototype tools that can be run on the die-cast machines. This makes possible the study of material flow throughout the die, formation of hot spots and soldering, the effectiveness of cooling channels, ejector pin layouts, vortices, overflows, gating and the list goes on. By changing laminates many iterations can be carried out before the final die design is set.

The program of research has taken four routes to achieve the aim of viable laminate tooling for pressure die-casting. These routes are:

- Die design considerations and selection of suitable sheet material.
- Testing laminate stacks against failure through thermal cycling/stress.
- Assessing the fundamentals of laminate die behaviour to withstand deflection and ingress of molten aluminium.
- The bonding of laminates in extreme environments.

There are various ways that a laminate tool can be constructed and so the first stage in this investigation was to consider the design implications when constructing a laminate tool. Time was also spent, establishing suitable sheet material and sheet thickness for use in these applications. After considerable effort all test dies are now constructed from 1 mm thick, cold rolled, H13 tool steel. Sources in both Japan and Austria can supply material with reasonable notice.

The second route was to look at the behaviour of laminate structures when used in pressure die-casting. This work has been done in conjunction with the United States Committee for Automotive Research (USCAR)' The third route forms the basis of fundamental research into laminate die behaviour under extreme conditions such as those found in pressure die-casting [10]. The fourth route is underway in conjunction with GEC Marconi, Hirst Division[11], and explores the bonding of laminates in a die.

CONCLUSIONS

Where large tools or prototypes are required the use of cut laminates offers a cost effective and fast method to get to the final design. Computer modelling is becoming increasingly more available to the designer but there is still a long way to go before it becomes a reliable modelling tool.

At present there is not considered a substitute for a test rig. Companies like Ford have long realised that a fast way to mock up the cooling assembly on an engine block is to construct the part from slices of steel that have been bonded together. Where an aesthetic finish is not essential and large scale is required, at present, there is no real substitute for the laminate structure.

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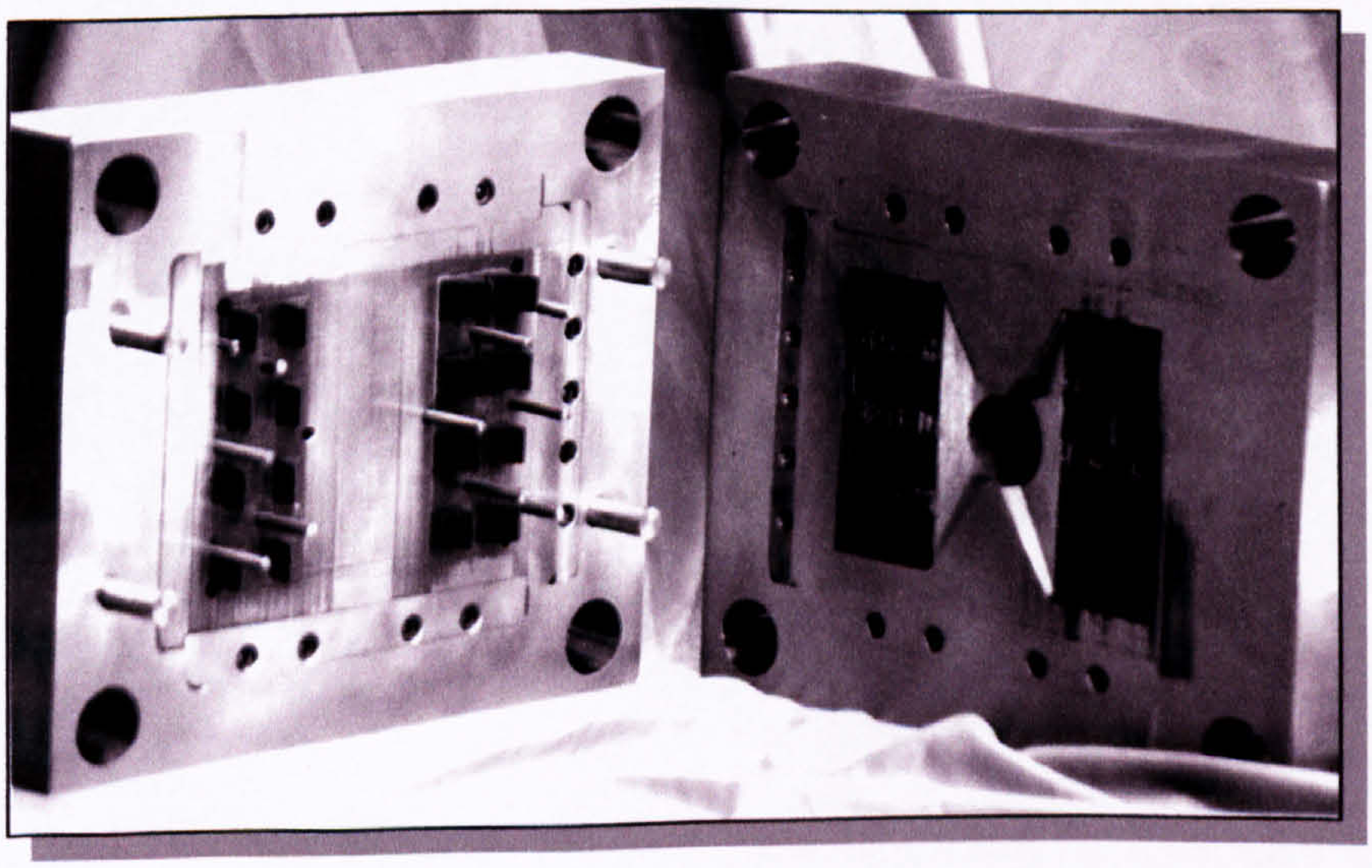

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